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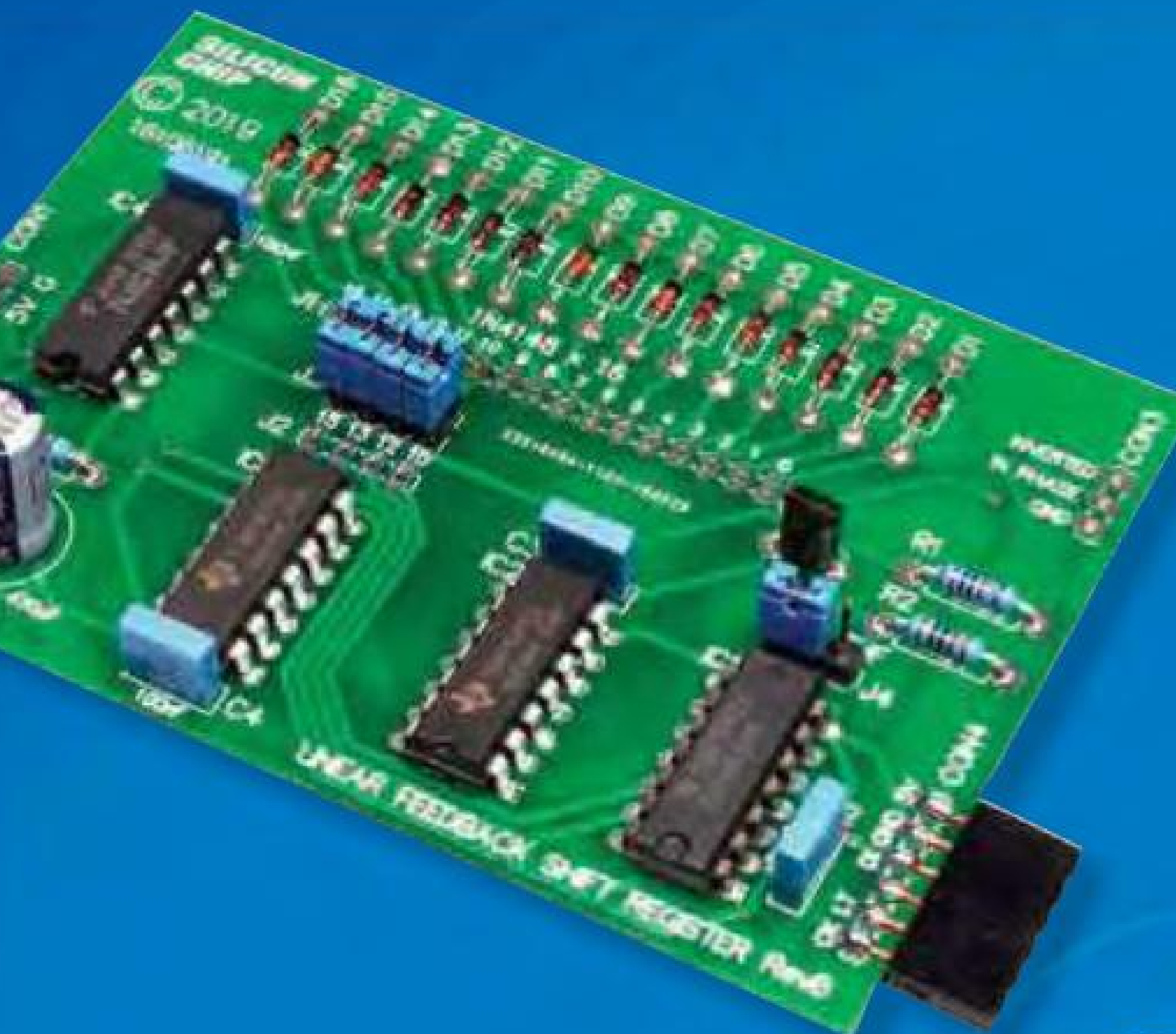
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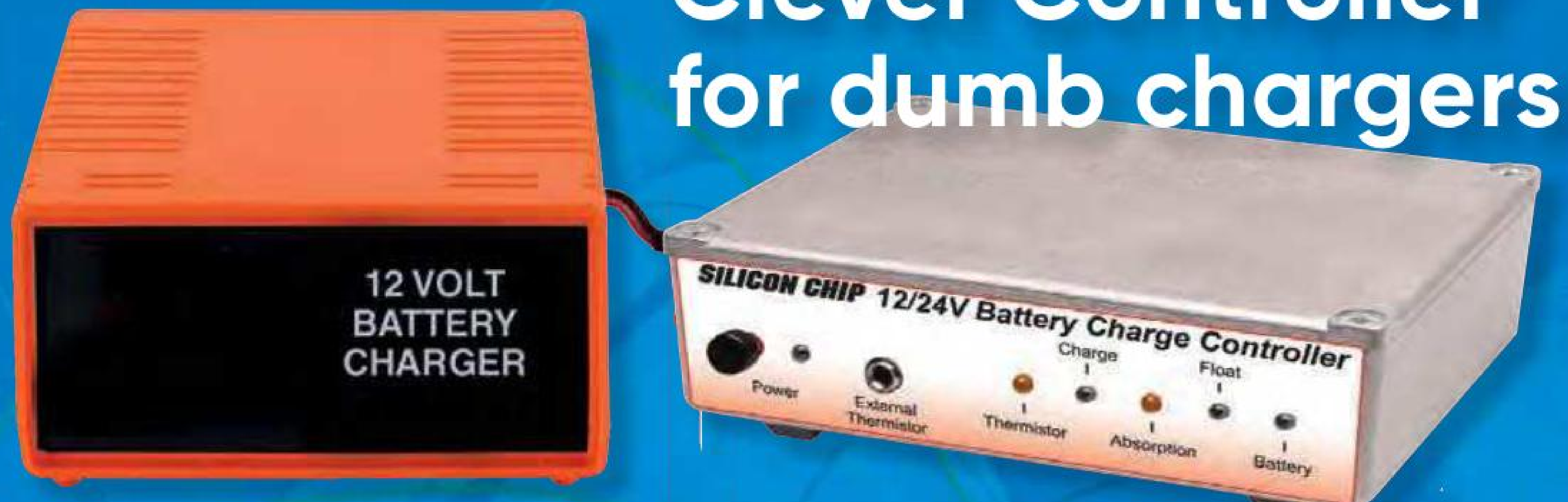
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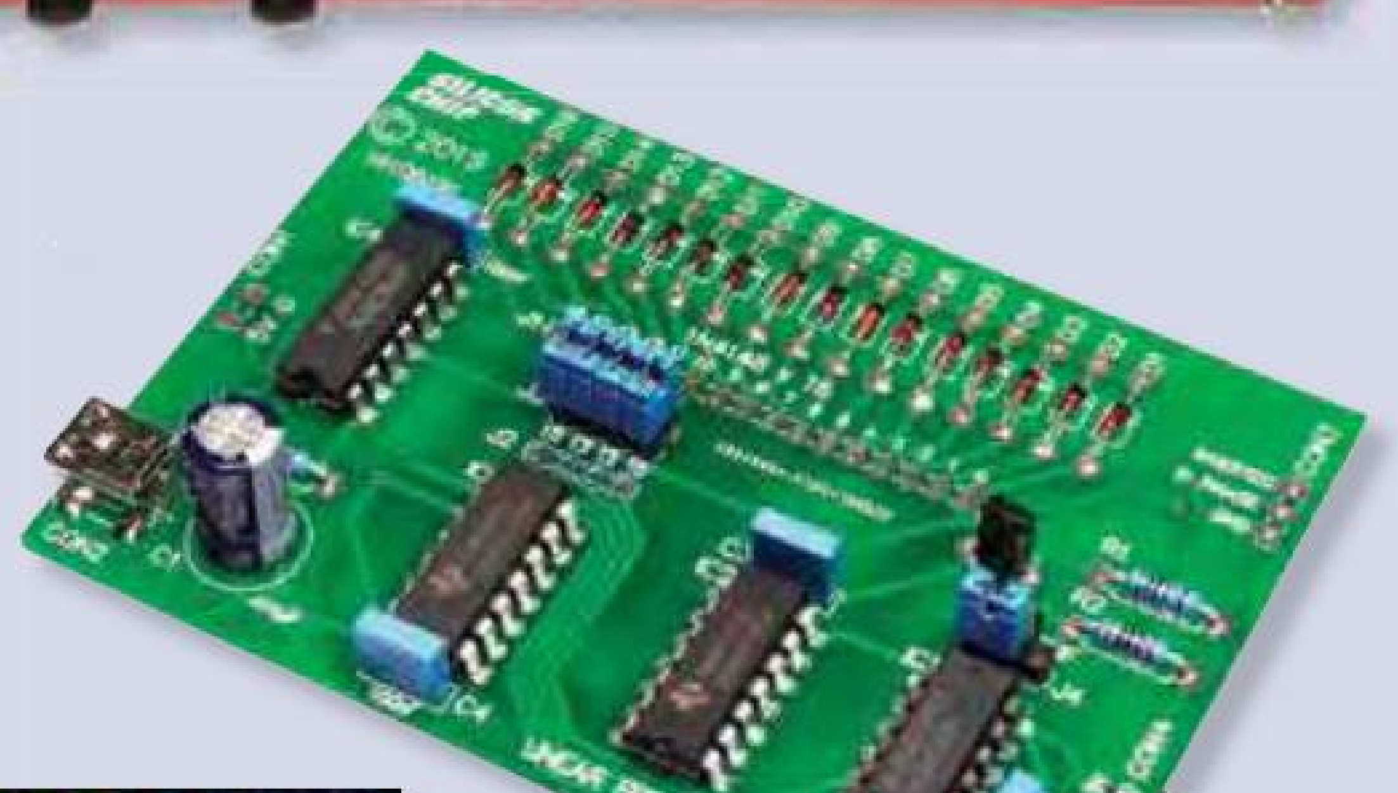

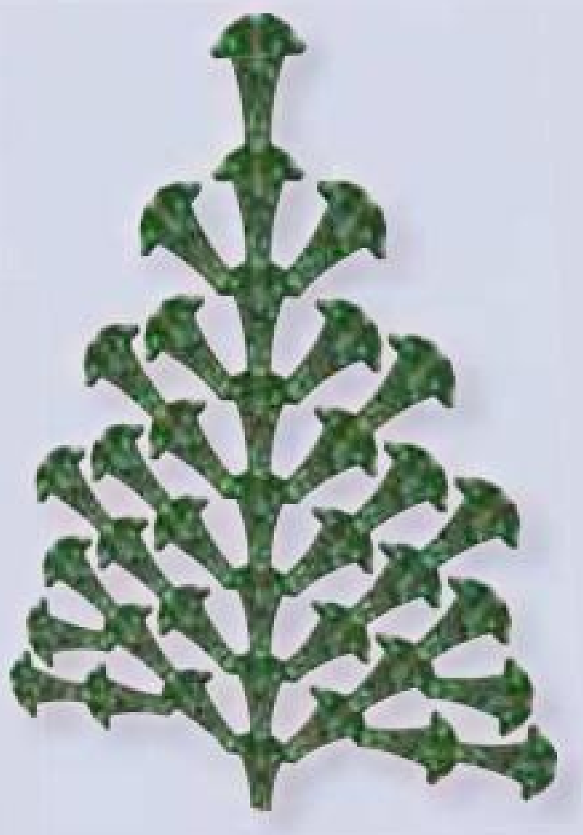

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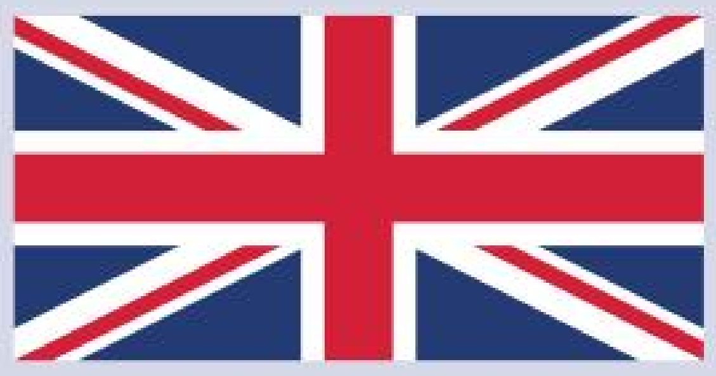

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WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

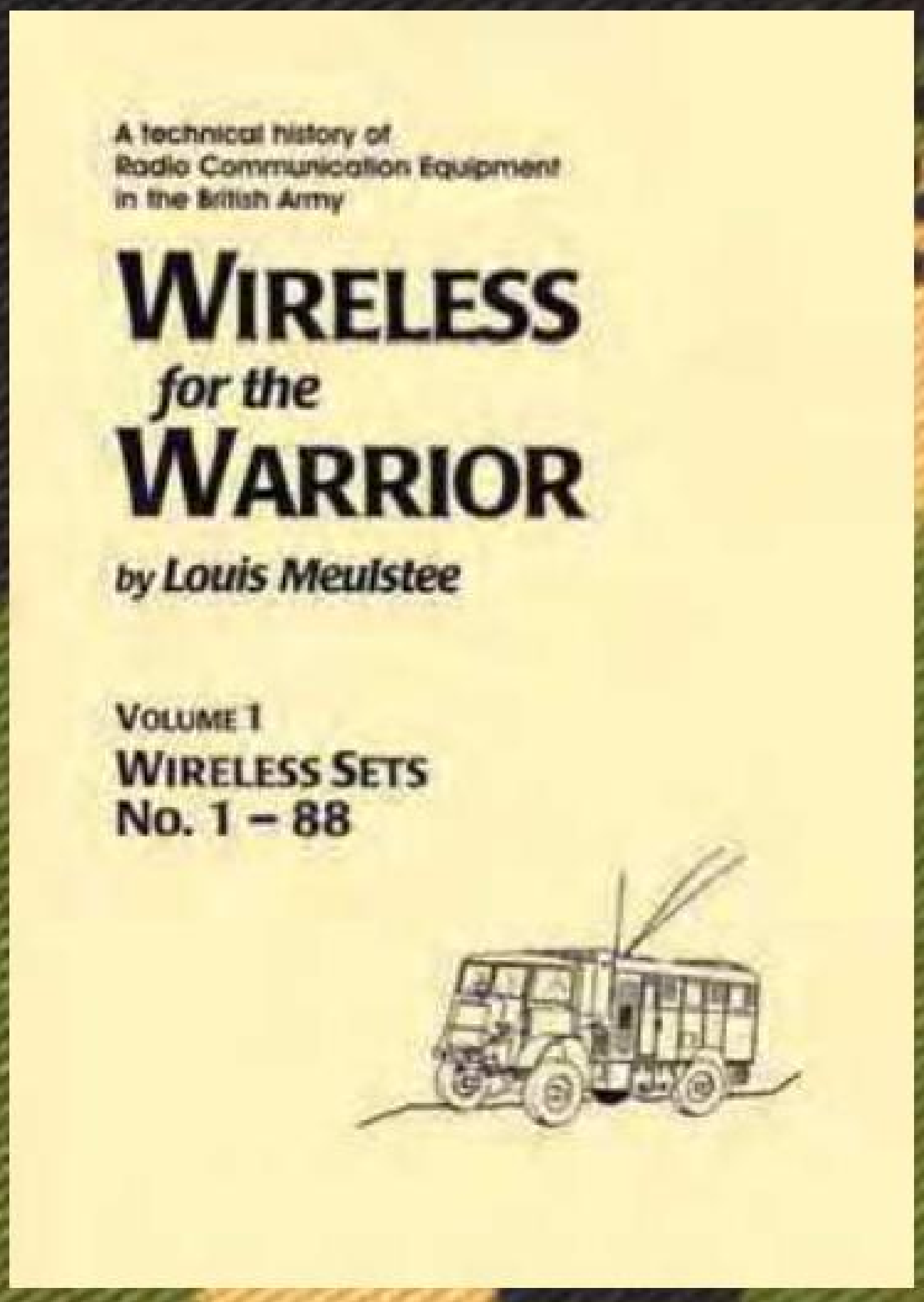
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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WIRELESS
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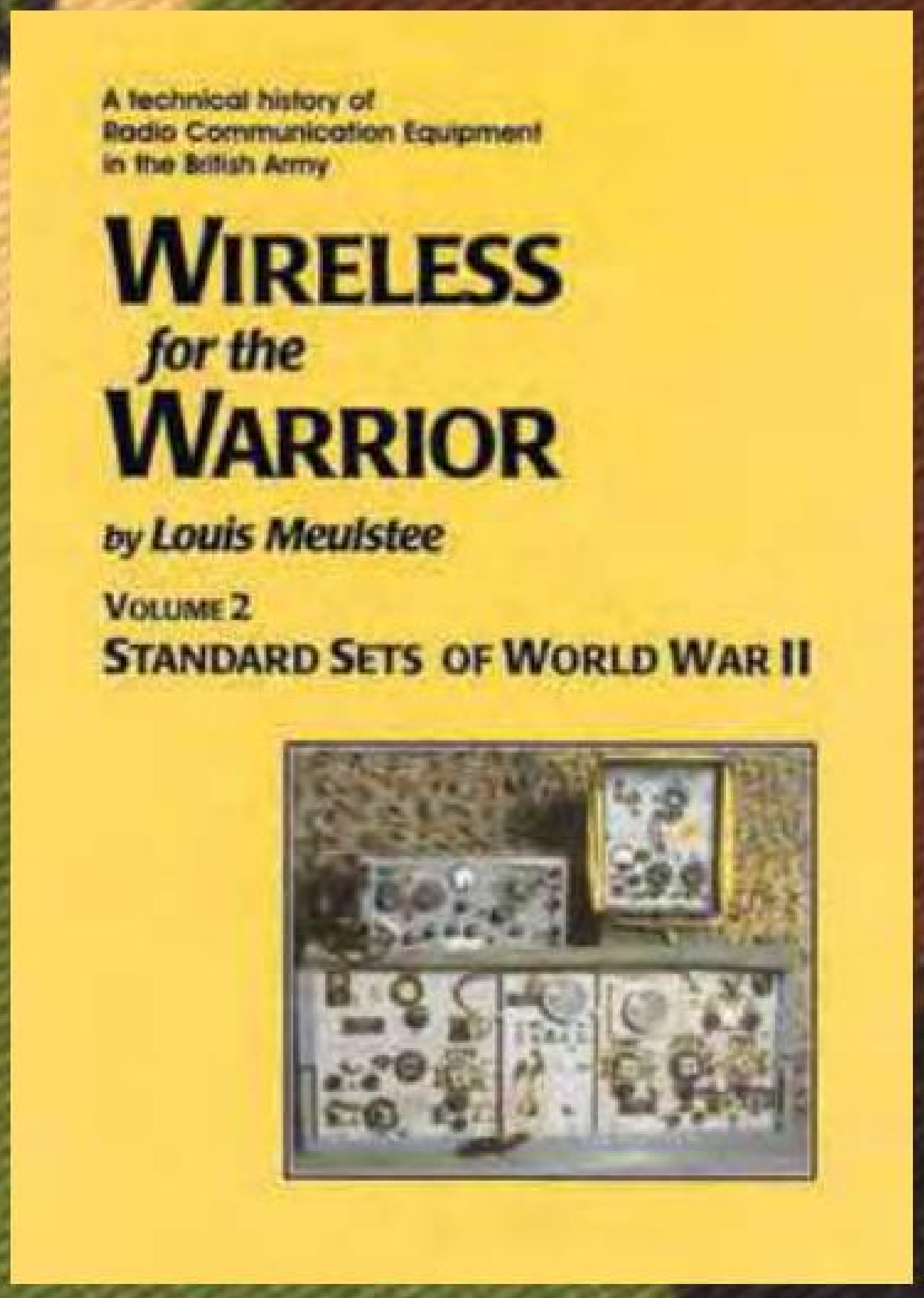

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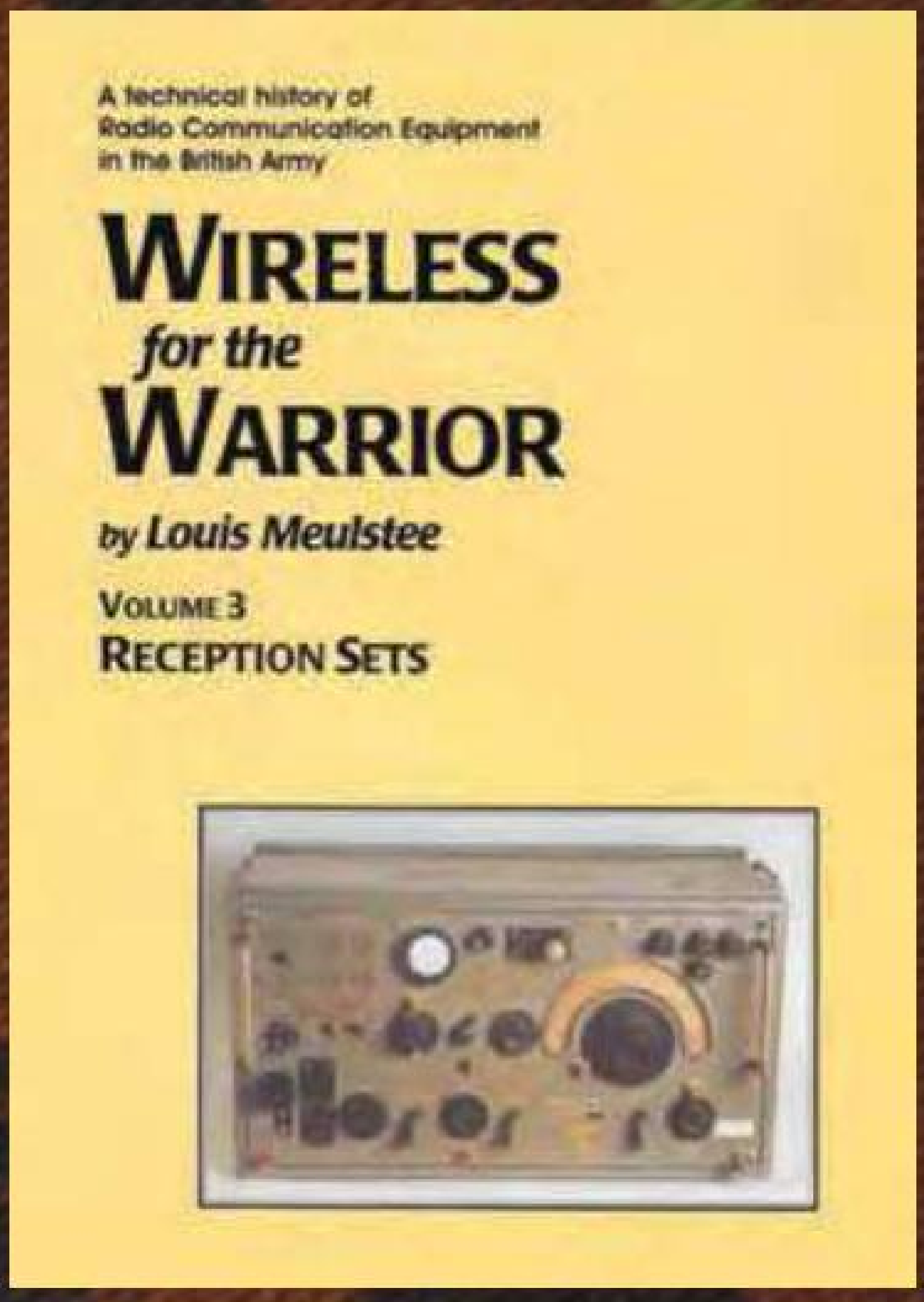

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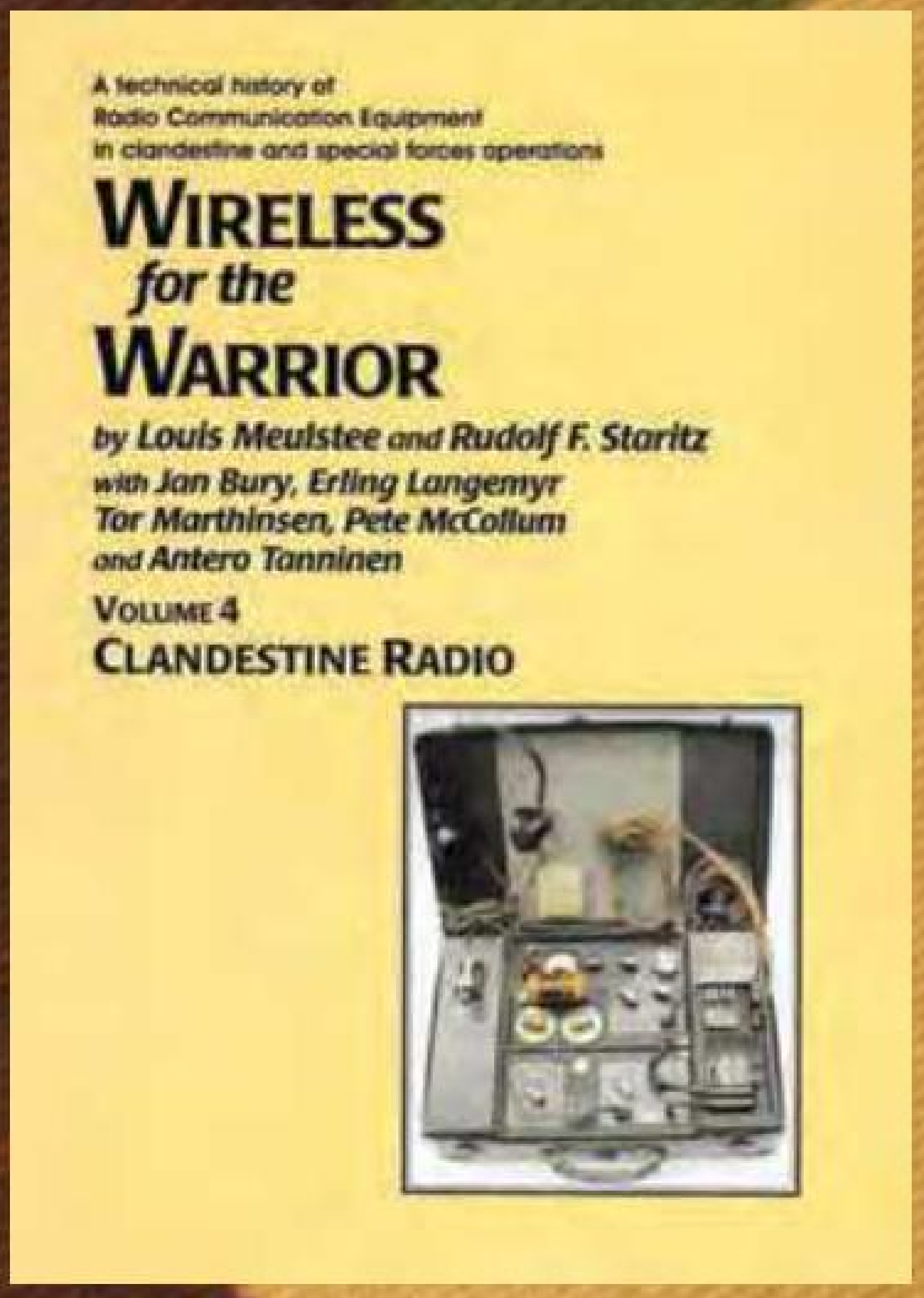

A technical history of
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in clandestine and special forces operations

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All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.

A number of projects and circuits published in *Practical Electronics* employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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Getting the balance right

'Time flies' – I know, this is not news, but still, I find it hard to believe that this issue is my 24th as publisher. The last two years really do seem to have just flown by. Although anniversaries are largely arbitrary, this does seem like a good opportunity to ask you for your opinion of what you like (and dislike) in *PE*; in other words, what you'd like to see more of, and what you skip over.

Probably the toughest editorial task has been getting the balance of the magazine right. There are many conflicting demands and requirements from readers who range from absolute beginners to seasoned professionals and educators. Some of you are diehard analogue fans, others enjoy adding a microcontroller to every circuit imaginable. We have project builders who each month order an impressive number of PCBs, and there are others who simply want to read and learn how things work.

Everyone's background is different, and impressively, we have many subscribers for whom English is not their first language. Understanding electronics can be challenging enough without having to wade through a foreign tongue – so we do appreciate all the extra effort made made by our many subscribers from the distant corners of the globe.

Wherever you are, whatever your level of training, education or interest, we want to hear from you. It is feedback that lets me and our talented writers get a feel for what you want to read in *Practical Electronics*. Do please let us know if you have any comments or ideas. We can't accommodate every suggestion, but when we can, we do – this month's *Circuit Surgery* being a nice example of a reader making a suggestion which became the focus of a whole article.

Ideas, comments, criticism are always welcome – just send us an email: **pe@electronpublishing.com**

Is it too early to mention Christmas… again?

Well, it's clear you like LEDs and Christmas trees! We ordered several hundred little PCBs for last month's *LED Christmas Tree* project, and we sold them all. More are on their way, so if you fancy something inexpensive, fun, festive and electronic then do see the special offer on page 33.

Keep well everyone

Matt Pulzer

Publisher

The **Fox** *Report*

Barry Fox's technology column

Smart meters – for whose benefit?

The energy companies are doubling down on their push for consumers to install 'smart' meters for gas and electricity. It is easy to see why. If meters in homes automatically send readings to their energy suppliers, by dedicated cell phone data link, the suppliers no longer need to pay humans to travel and read home meters (repeatedly, if no one is home). Furthermore, if consumers do not pay bills, their supply can be remotely shut off (without the expense of deploying workmen with shovels to dig the road and cut the street connection).

Smart meters

SMETS1 (First Generation Smart Metering Equipment Technical Specifications) systems have been fitted in homes since 2013, and offer the energy suppliers another bonus. They send the data direct to the supplier. This makes switching energy supplier more difficult because with a new supplier the 'smart' meter may turn 'dumb', much like a Smart TV that no longer updates its iPlayer or Netflix apps.

New SMETS2 second-generation hub devices have been rolling out since 2018. These send gas and electricity meter readings to a data centre that then forwards the information to the appropriate suppliers. However, some suppliers have been using up their old stock of SMETS1 hardware.

In theory, SMETS1 devices may be software upgradeable to make them 'cross-supplier compatible'. But don't bet on it. My SMETS1 electricity meter hub can't send gas readings, so I needed a new SMETS2 gas hub which now sits alongside the SMETS1 electricity device.

Isn't all this evidence of clumsy planning? You can be the judge of that, but do bear in mind that most homes use both gas and electricity, and also, consumers may want to change suppliers. Neither of these are hardly new nor radical ideas.

Smart? The author's two meters needed for gas and electricity.

Patronising and misleading

There is currently a publicity push for smart meters. The voice-over for TV adverts from Smart Energy GB, 'the UK Government-backed campaign for a smarter Britain',

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encourages viewers to 'join the quiet revolution' by installing smart meters. To sell the message, the voice-over – which resembles an adult talking down to a toddler – claims that 'home by home, something extraordinary is happening (and) smart meters are helping to upgrade Britain's outdated energy system'. The voice accompanies visuals showing wind farms generating electricity.

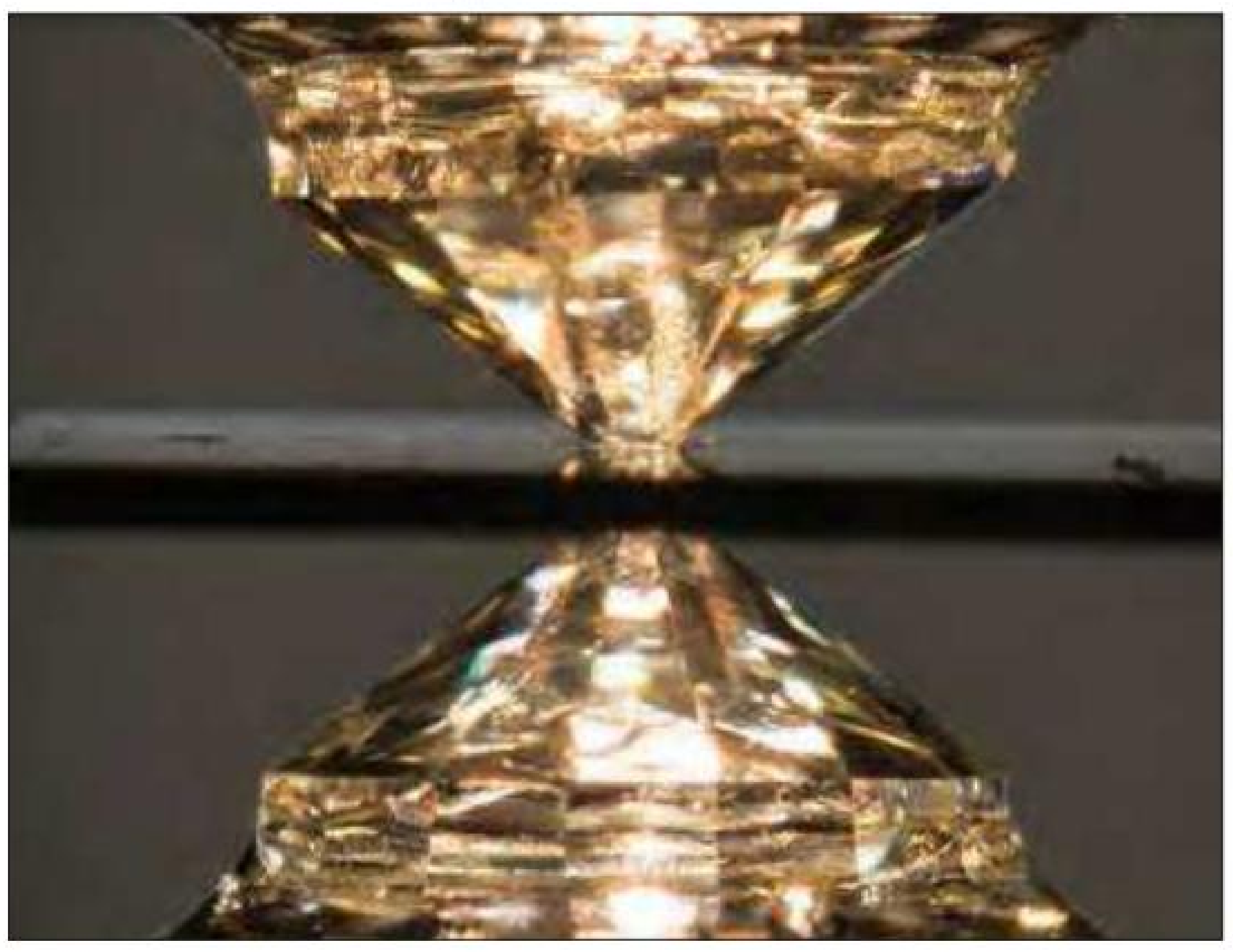
Honest and truthful?

As a test case I have complained to the ASA (Advertising Standards Authority) that tying the installation of smart meters in homes to the use of wind turbines in fields or offshore is misleading given the lack of any explanation in the adverts as to why this might be so.

I have reminded the ASA that the power companies do not mention their own very good reasons for wanting consumers to install smart meters; eg, the companies no longer have to employ human meter readers, they can remotely disconnect naughty consumers, and the installation of first-generation meters without automated upgrading to second-generation capability is an obstacle to changing suppliers. So, all in all, it is misleading to lead us to believe that the installation of wind turbines is dependent on the installation of smart meters in homes.

It will be interesting to see how the ASA handles this case (see: **http://bit.ly/pe-dec20-ASA**).

Room-temperature superconductor


Diamonds are a researcher's best friend, helping achieve room-temperature superconductivity at great pressure. (Credit: J. Adam Fenster / University of Rochester)

A new record has been set in the pursuit of 'high'-temperature superconductors – an astonishing 15°C, or 'just about' room temperature, report researchers from the University of Rochester (New York, US).

Superconductive materials were once confined to research labs with access to cryogenic facilities. Liquid nitrogen, or even colder liquified gases were needed to cool and persuade materials to exhibit zero resistance to electric current. However, using new materials, in recent years the temperature at which this phenomenon works has steadily risen from ultra-cold, to chilly and now almost warm. Researchers are not popping the champagne just yet – while the operating temperature has risen, so too has the required pressure. To achieve superconductivity the Rochester team's sample of hydrogen, carbon and sulphur had to be crushed between diamond anvils to the kind of pressure found at the earth's core.

Nevertheless, it's several more steps in the right direction towards the goal of achieving lossless power distribution, low-cost maglev transport and faster, more efficient electronics for digital logic and memory device technology.

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IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
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Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
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HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
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Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio Communications Test Set – £800

Triumph or travesty?

Techno Talk

Mark Nelson

Spoiler alert: This article revolves around a minor news story published in late September this year. Even then, it was not headline news, and was soon forgotten. It does, however, involve practical electronics, with implications that are broader than you might imagine, calling into question the competence of Britain's leading broadband infrastructure provider. Am I over-reacting? Read on and see what you think.

One of the first things that reporters and media relations people are taught during training is that today's news stories will be wrapping fish suppers tomorrow. Old news is soon forgotten, and for people and organisations castigated in those stories, this is no bad thing if unwelcome news can be buried rapidly. Another lesson taught early on is that when you're in a hole, you stop digging. And you certainly don't shout about your predicament.

Despite these truisms, on 22 September, BT Openreach's press office announced that its most experienced engineers had taken 18 months to solve a mystery fault that had plagued the broadband connections of residents living in a rural village in mid-Wales. Openreach gushed: 'For months the inhabitants of Aberhosan – along with some neighbouring communities – have endured poor broadband connectivity and slow speeds every morning at 7am, despite repeated visits by engineers to fix the fault. Frequent tests proved that the network was working fine and local engineers even replaced large sections of cable that served the village, but the problems remained.' – see: **http://bit.ly/pe-dec20-open**

World-class service in action?

Excuse me, is Openreach – which boasts on its website of providing world-class customer service – really unable to clear a fault in under 18 months? Evidently so. Yet, the company's website also declares, 'Data is such an essential part of consumers' lives they have high expectations when it comes to service. To make sure Openreach can meet them, we have quality of service standards – values we measure ourselves against to track how we're performing.' That the company considers taking 18 months to clear a fault as a matter for self-congratulation strikes me as, well, risible.

After studying 20 different reports on this farrago, I can only say that not one of them stacks up. The Openreach version simply spouts waffle about a maladjusted television receiver without explaining how a short burst of electrical interference can block ADSL broadband service throughout a whole village as well as at properties outside the village. The broadband technology in use must be pretty feeble if is so poorly shielded against a burst of interference. Of course, none of the media reports describes how long the trouble persisted each day. Given that the problem recurred every day at the same time, presumably the outage was only temporary and cleared itself rapidly, in good time for the same problem to recur the next day.

Mains-borne interference?

Openreach finally traced the source of the interference to an 'old' television receiver, but given that mid-Wales was converted from analogue to digital television in 2010, the oldest tellies in use there cannot be more than ten years old. So how can an ancient TV still be in use if it's an old analogue UHF set (unless the viewer is using a Freeview box to convert digital to analogue). In that unlikely case, it is indeed possible that the television's power supply might have caused mains-borne interference from the TV's power supply. The Philips G8 model of the 1970s, for example, was notorious for radiating nasty 25Hz 'hash' over wide areas. But are we really suggesting that this noisy telly was adjacent to the village distribution cabinet and was fed from the same supply feed and phase? If so, perhaps Openreach should fit better mains filtering on incoming mains feeds – and provide earthed screening inside their cabinets.

In any case, as a forum poster at Digital Spy (**http://bit.ly/pe-dec20-dspy**) points out, Openreach could have looked at the DSLAM logs, to see exactly when the lines were affected with loss of (or reduced) sync. The same thread states that *ITV Evening News* had interviewed villagers who said their broadband was *still* misbehaving – and that if anything, it had actually got worse! One of them added that the outage occurred even when the owners of the unruly telly were away on holiday – spooky or what?!

Precise explanation

Openreach identified the fault as 'a phenomenon known as SHINE (single high-level impulse noise) where electrical interference is omitted from an appliance that can then have an impact on broadband connectivity'. Someone at Openreach clearly doesn't know the precise difference between 'omitted' and 'emitted'! The Zen Internet website explains more precisely that SHINE occurs when interference is generated as a burst – for example, when a device is powered on or off. As a result, disconnections or line errors may result at the time a device is switched on or off.

Incidentally, there is another kind of interference affecting broadband called REIN (repetitive electrical impulse noise), which, as the name suggests, occurs persistently. This will typically result in disconnections or line errors while the interfering electrical device is in use and at worst, may prevent any connection being established at all. In either case, come REIN or come SHINE, broadband users are likely to see persistently slower data speeds while the automated systems work to mitigate the interference by throttling back the maximum connection speed.

Good news and bad

The best comment was on the **Hackaday.com** website: 'We'll say one thing for the good people of Aberhosan: they must be patient in the extreme to put up with daily Internet outages for 18 months.' And as a reward, Aberhosan residents will soon be connected to fibre, as part of Openreach's work with the Welsh Government to further expand the fibre broadband network in rural Wales.

Meanwhile, in other news the UK is now among the slowest countries in Europe for broadband download speeds. Analysis and advice organisation **www.cable.co.uk** reports that with an average (mean) broadband download speed of 37.82Mbit/s, the UK comes 22nd out of 29 western European countries. In global terms the UK comes 47th, against 34th last year. Nothing to be proud of.

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Net Work

Alan Winstanley

This month, *Net Work* looks at the rise of the most lucrative of all electronic products – the car. From 'joke' to must-have purchase, the electric car is a revolution happening right now.

Almost 40 years ago your scribe could sometimes be seen hanging on for grim death at the wheel of an Austin MG Metro, a cleverly designed compact hatchback dressed up with fancy British 'MG' sports car trimmings. Sadly, the car's lineage would go the way of the rest of the British motor industry and MG eventually fell into the hands of China's Nanjing Auto before merging with state-owned giant Shanghai Motor (SAIC). For anyone interested, there are more Metro reminiscences at: **https://en.wikipedia.org/wiki/Austin_Metro**

Under new ownership

SAIC sells huge numbers of cars locally under its Roewe brand (a sound-alike nod to Britain's old 'Rover' marque) but elsewhere – including Britain – the much-missed MG moniker is once again adorning the front grilles of a range of medium and large SUVs that originated in China. When trying to garner sales, having a historical brand like MG on a swing-ticket can only help to establish credibility. Visitors to MG India's website (**www.mgmotor.co.in**), for example, are greeted with a full-on banner exclaiming 'Morris Garages since 1924' alongside plenty of MG heritage and folklore. It would be churlish and naive to criticise SAIC for rescuing and exploiting the MG brand while claiming to be a '94-year-old start-up', as MG India's website proudly boasts. Sales in India of MG-branded cars are storming ahead, which also illustrates the extent of China's soft power reaching slowly but surely around the world.

SAIC faces the task of cashing in on the past while also leaving it behind. Chinese rival Geely Auto is privately owned and while their cars' styles might not suit Western tastes, they also own Sweden's Volvo and they design cars in Gothenburg. Many years ago, I visited 'Volvo City', but now, under Chinese ownership, Volvo has stopped the development of petrol and diesel cars as it moves towards electric vehicles instead. Geely has ambitious plans for some technologically advanced vehicles, starting with its *Xing Yue* SUV designed in Sweden (see: **http://global.geely.com/car/xing-yue/**).

Plenty of ambition and innovation are apparent at a revitalised MG Motors though, and although they have been a relatively rare sight on Britain's roads, this reborn car brand has formidable resources behind it and has set its sights on the future of electric vehicle (EV) ownership. In the UK, MG Motor ('Britain's fastest growing car brand') recently enjoyed its best ever month with sales up 50% year on year, they say, despite a general market malaise and temporary showroom closures. Their sales up-tick is attributed to the electric MG ZS EV, and one in three MG sales were electric cars, selling just over 3,700 in September. It's good news but, looking at the bigger picture, figures from the UK's Society of Motor Manufacturers and Traders (SMMT) show that 1.3 million vehicle sales of all types have been sold so far in 2020 and a quarter of them were either electric or electrically assisted. MG has some appealing electric cars to offer and, helped by the British branding, hopes to catch the tide of electric car sales in the UK.

Going electric

The sun is gradually going down on the era of fossil-fuelled automobiles, and clearly the car's future is in battery power allied to aspirations for green electricity generation. Consumers are being bombarded with images of zero-emission, high-tech electric vehicles humming silently along, or city cars plugged into readily available charging points. Extra benefits of driving these zero-emission, all-electric cars in the UK include annual tax-free licensing and concessionary car parking as petrol/diesel cars become the bad guys. For many of us, electric vehicles currently pose some drawbacks, including their limited range and the dearth of charging stations, plus the time needed to charge them, which has given rise to the terms 'range anxiety' and 'charging anxiety'. And this new technology comes at a hefty price: even a compact hatch like the Vauxhall Corsa-E 5-door weighs in at about £31,000 ($40,000) and that's after a £3,000 plug-in car grant (PiCG). This all-electric car has a range of [up to] 209 miles from its

A revitalised MG Motors is poised to join the electric vehicle revolution. Shown here, the MG ZSEV electric SUV.

The Honda e all-battery electric city car hails the future of BEVs with some remarkable engineering and design ideas.

The Honda e interior is fitted with a full-width all-electronic dashboard with LCD screens showing the rear view.

50kWh lithium-ion battery. More details are at: **http://bit.ly/pe-dec20-vaux**

Electric car jargon

We will soon specify cars not in horsepower but in kilowatt-hours, and no doubt electric vehicle ownership will bring with it a raft of considerations about refuelling and running them, along with some confusing new jargon. For readers who are on the cusp of considering their first electric vehicle, here's an overview of some key aspects.

HEV – a hybrid electric vehicle is equipped with a conventional petrol or diesel engine, but it also uses regenerative braking or has its own generator to recharge an on-board battery. This can provide a few tens of miles of zero-emission, electrically powered motion before the engine kicks in again. The industry is falling over itself to launch HEVs which may be ideal steppingstones for motorists who are buying their first electric car. There's the Hyundai Ioniq and Kona, Renault Clio E-Tech Hybrid, VW Golf and Passat, Toyota Yaris, CH-R or Corolla… and more to choose from.

MHEV – a so-called mild hybrid electric vehicle is a scaled-down HEV with a smaller battery. The electric motor doesn't propel the car directly but instead complements the engine to aid efficiency, also enabling the engine to switch off during braking, cruising or when motionless. To an onlooker it seems the auto industry has obfuscated the MHEV segment somewhat, which suggests that MHEVs are currently a work-in-progress. Even so, sales of MHEVs have accounted for 121,000 diesel and petrol cars sold this year. Examples of MHEVs include the Hyundai 48V Hybrid Assist and Kia Sportage 'Ecodynamic'.

Rear-facing cameras in door pods act as 'wing mirrors'

PHEV – a plug-in hybrid electric vehicle has both an engine and a larger-capacity battery that can also be topped up with an external charger lead at home or at a charging station. The electric-only propulsion range of a PHEV is typically in the medium tens of miles, and the petrol/diesel engine propels the car the rest of the time, which gives the car a useful range. Examples include some Hyundai Ioniq models, Peugeot 3008 and Ford's Kuga. About 42,000 PHEVs have been sold so far this year, says the SMMT, compared with 84,000 HEVs.

BEV – a battery electric vehicle has no internal combustion engine and depends on battery power for propulsion – like the Vauxhall Corsa-E, MINI Electric or Peugeot e-208. Present-day mainstream BEVs have a typical round-trip range of 150-200 miles or so. (I say 'round trip' because, having travelled somewhere, you must plan to get home again!) Some 66,000 BEVs have been sold so far in 2020.

Japan's Honda often does its own thing just because it can, and Honda's new and eagerly-awaited all-electric city car – the Honda e – is no exception. It has already won plaudits for its advanced and totally out-of the box, minimalist design. Aimed squarely at urban motorists and commuters, the Honda e BEV claims up to 137 miles maximum range and it has a 30-minute rapid charger. The car is laden with technology inside, with a full-width electronic dashboard, voice recognition and rear-facing cameras instead of wing mirrors. Rear-wheel drive dispenses with the need for a centre console. As we gradually move towards the era of all-electric motoring, six electric vehicles are promised by Honda over the next three years, starting with this Honda 'e' BEV at £26,660 for the 100kW version and £29,160 for the higher-spec. 113kW model. More details and a gorgeous website presentation are at: **http://bit.ly/pe-dec20-honda**

Half of us are not yet ready for the proposed 2035 ban on new petrol, diesel and hybrid car sales in the UK, says the SMMT. There are plenty of wrinkles in the ecosystem still to iron out and the purchase price of electric vehicles is still high (but falling – production-cost parity with fossil-fuel cars is estimated to be just five years away), but these latest developments are sure signs of things to come and the future for all-electric motoring has never looked more attractive or exciting.

A HeimLink manouevre

Back in September's column I offered a few practical tips on installing an IP security camera at home, highlighting some of the current trends in domestic network cameras, including standalone rechargeable and solar-boosted models. If quality and reliability are needed, there is probably no substitute for hooking a dedicated 'cabled' CCTV to a hard-disk recorder, but networked cameras provide a cheap home solution for anyone needing basic surveillance around their property. One of the biggest issues is that of wireless coverage: many IP cameras only operate on Wi-Fi so they must obviously be within reach of a wireless hotspot, repeater or router, not forgetting a power outlet too. Another common problem is that of 'lag', where network bottlenecks mean that events may not be captured until several seconds have elapsed, when it may be too late to

The HeimVision HM311 is a budget-price IP camera with Wi-Fi and Ethernet, plus two LED spotlights

act. If nothing else, though, IP cameras let you generally keep an eye on things and some cameras record to an onboard microSD memory card, or there is the option of uploading to a paid-for cloud-based storage service.

While many such cameras look the same, one or two stand out from the crowd, and one brand that I tried recently was the budget-priced HeimVision HM311. Usefully, this 3MP 110°-viewing-angle camera offers both Wi-Fi and Ethernet network connections; has a built-in memory card slot; speaker and microphone; and, unusually, also incorporates a pair of high-brightness LED lamps that can be switched on remotely or instead be motion-activated. The camera AI can record automatically if it recognises human shapes or movement in predefined zones (untested by the author), and in 'alarm' mode it can optionally sound a siren noise over its small speaker. Also available is their cloud-based storage for a monthly fee.

Costing well under £40, it was worth a try and in practice the set-up went better than expected. The English instructions were very well written, although some minor discrepancies were found in practice. It can be set up on a network by scanning a QR code, and here was the biggest dilemma: the proposed location was on an outdoor block more than 50m away, beyond the reach of Wi-Fi. It's also pushing things to run an Ethernet cable that far. The solution was, once again, to set up powerline communications to run a network over the ring mains with a legacy Devolo adaptor described in previous columns. One such adaptor (the MT2516) has two Ethernet ports and a mains through-socket (but no Wi-Fi), which I used to both power the camera and hook it to the mains-borne network with an Ethernet lead. The camera's bulky connection block carries Ethernet and DC power leads plus a reset switch on a short weatherproof flying lead. Note that DC (5.5 × 2.1mm) extension cables are available on eBay.

Out of interest, I tested my idea using a very long mains extension reel trailing down to the end of the garden, and after installing the HeimLink app on a smartphone I was pleasantly surprised by the results. The picture was very good although there was some network lag (three seconds or more) making fluent two-way speech communication nearly impossible. The 'supervisor' app logins gave full control, including remotely activating the LED lights successfully, and it was also possible to log into the app on a separate device in 'guest' mode or view the picture in a web browser instead. If you're looking for an outdoor IP camera, the HeimVision HM311 is well featured and may be worth trying and the price (£35 typical) isn't out of the way, bearing in mind all the likely installation wrangles that I've outlined before. It's available on Amazon.

Getting Ten of the best

Now a quick roundup of other news. After years of faithful service, the time finally arrived for Windows 7 to be banished from the author's PC, and Windows 10 is now installed and running on a new motherboard and disk. The migration went surprisingly well, although casualties included an expensive legacy Wacom graphics tablet and a Logitech webcam that have bitten the dust.

For those who are still using Windows 7 or 8, it has been found that Microsoft's free Windows 10 upgrade offer still holds true as at mid-October, so an existing Windows 7 or 8 activation code can be used to update it or, in my case, create a clean new installation of Windows 10 Pro on an upgraded PC. Simply visit **http://bit.ly/pe-dec20-w10** and follow the links to create a USB installation media key (quite a lengthy process), then reboot the PC in question using that. No need to buy another licence!

With demand for rechargeable batteries for gadgets and electric cars skyrocketing, what better time to rediscover long-lost lithium deposits ready for extraction, which is what has happened in the county of Cornwall in south-west England. Cornwall is an area known historically for its tin, copper and cobalt mines (the famous 'Cornish Pasty' was baked to feed miners – see **http://bit.ly/pe-dec20-pasty**) and geoscientists are now examining the feasibility of extracting 'globally significant' quantities of high-grade lithium from geothermal springs that were first discovered back in the 1860s. Currently, Australia is the largest supplier of lithium in the world, followed by Chile and China, but if explorations prove viable, the UK hopes to establish a lithium processing facility of its own in three to five years.

Be your own 'Big Brother' – Ring is launching the Always Home Cam, a drone security camera that flies along a predetermined path around the home.

The Ring brand, best known for its video doorbells and now owned by Amazon, has announced a home security camera with a difference – the Ring Always Home Cam is a small drone camera that works with Ring Alarm and can patrol indoors to provide a streaming video feed during flight. It could be used to check on kids or pets, or ward off intruders. Ring is also working on car video alarms that monitors vehicles and alerts owners of break-ins. Sign up for details at **ring.com**

SpaceX has suffered delays with recent rocket launches due to bad weather interfering with the operation of drone ships that act as landing pads for the reusable launch stages. The US Transport Command is now investigating the feasibility of using Elon Musk's SpaceX space launch vehicles to deliver up to 80-ton consignments anywhere in the world in less than an hour. Subject to trials, a proof of principle could materialise next year.

That's all for this month's roundup – see you next month for more *Net Work!*

The author can be reached at:
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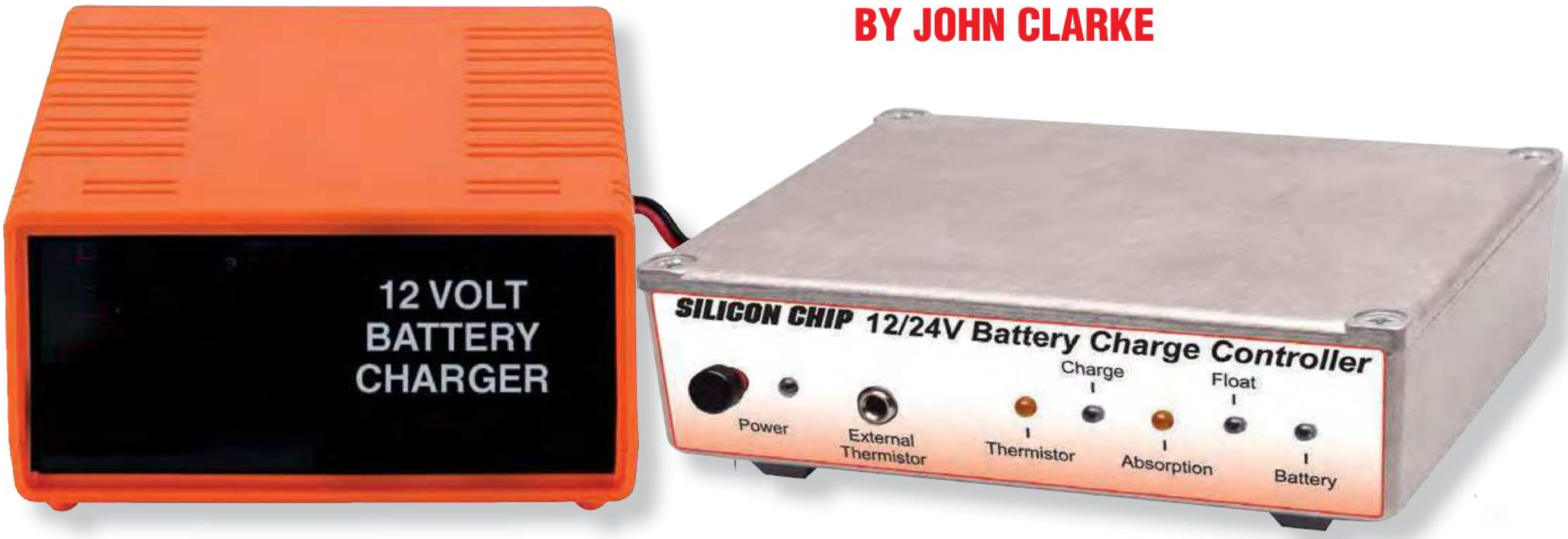
Clever Controller For a Dumb Battery Charger

BY JOHN CLARKE



Most cheap battery chargers – the type you might buy at a hardware store or auto retailer – are pretty dumb. As many people have discovered (because these chargers are so dumb) they can actually destroy the battery under charge! If you have one of these chargers, you can upgrade it to one with a clever controller, suitable for flooded lead-acid, sealed lead-acid (SLA) or even LiFePO$_4$ rechargeable batteries.

Many manufacturers' idea of a battery charger is a transformer, a diode or two and a pair of clip leads... and not much else. You may even have one of these sitting on a shelf in the garage. They're everywhere!

Sure, it will charge a flat battery but the chances are if you don't unclip it, it will keep on charging and charging and charging... until the battery electrolyte is boiled dry, the plates are buckled or, worst case, you have a fire on your hands that may be very difficult to control!

Our new *Charge Controller* is used in conjunction with one of these basic, low-cost lead-acid battery chargers. It transforms this 'dumb' charger into a more advanced device that can still charge at the same maximum rate, but also offers proper charge termination, float charging and temperature compensation. Since it's fully adjustable, it caters for the lithium-iron-phosphate (LiFePO$_4$) batteries that are starting to become available as a replacement for lead-acid types.

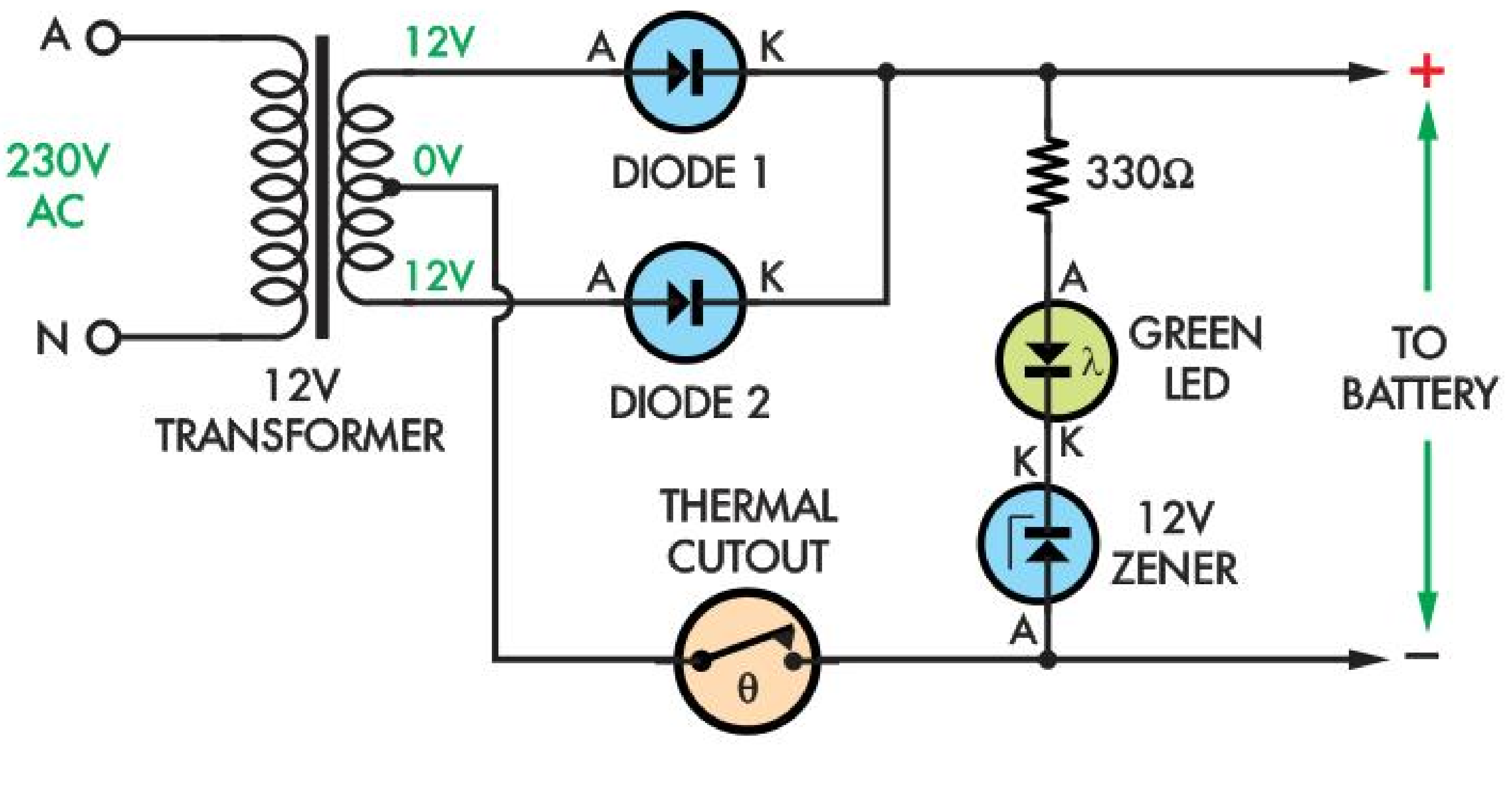
Compared to lead-acid, LiFePO$_4$ offers faster charging and discharging, more charge cycles, smaller volume and lighter weight, albeit at a higher cost.

Adding a fully automatic *Charge Controller* to a basic charger will also prolong the life of your batteries, and you can leave a battery on a float charge as long as you want, ready for use when required. LiFePO$_4$ batteries usually are not float charged, so you can disable that step for these batteries.

Basic charger flaws

The configuration of a typical low cost lead-acid battery charger is shown in Fig.1. It comprises a mains transformer with a centre-tapped secondary output. The output is rectified using two power diodes to provide raw DC for charging the battery. A thermal cutout opens if the transformer is delivering too much current.

Charge indication – if it is present at all – may be as simple as a zener diode, LED and resistor. The LED lights when the battery voltage exceeds the breakdown voltage of the zener diode (12V) and the forward voltage of the green LED (at around 1.8V). Thus the LED begins to glow at 13.8V and increases in brightness as the voltage



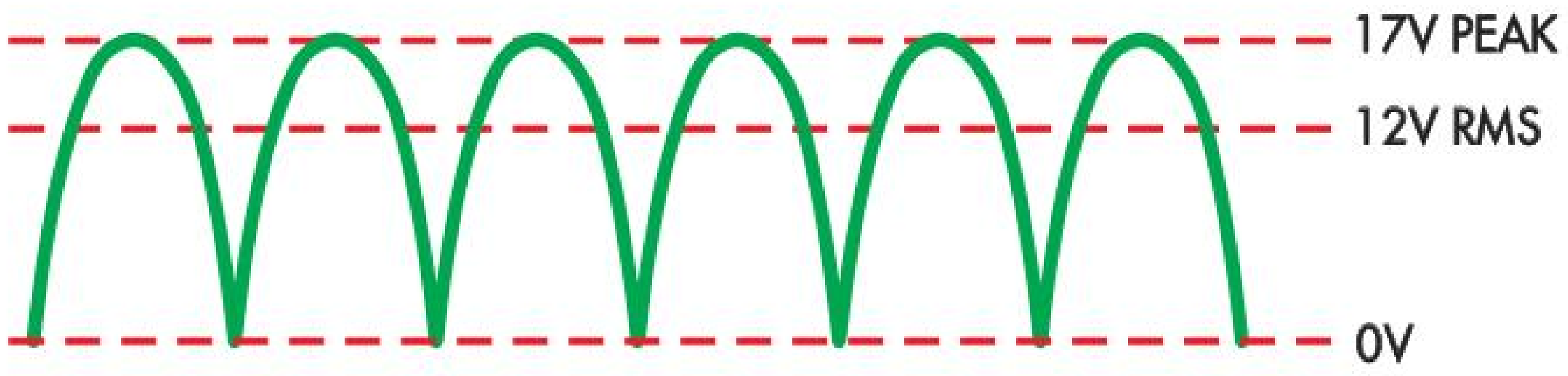
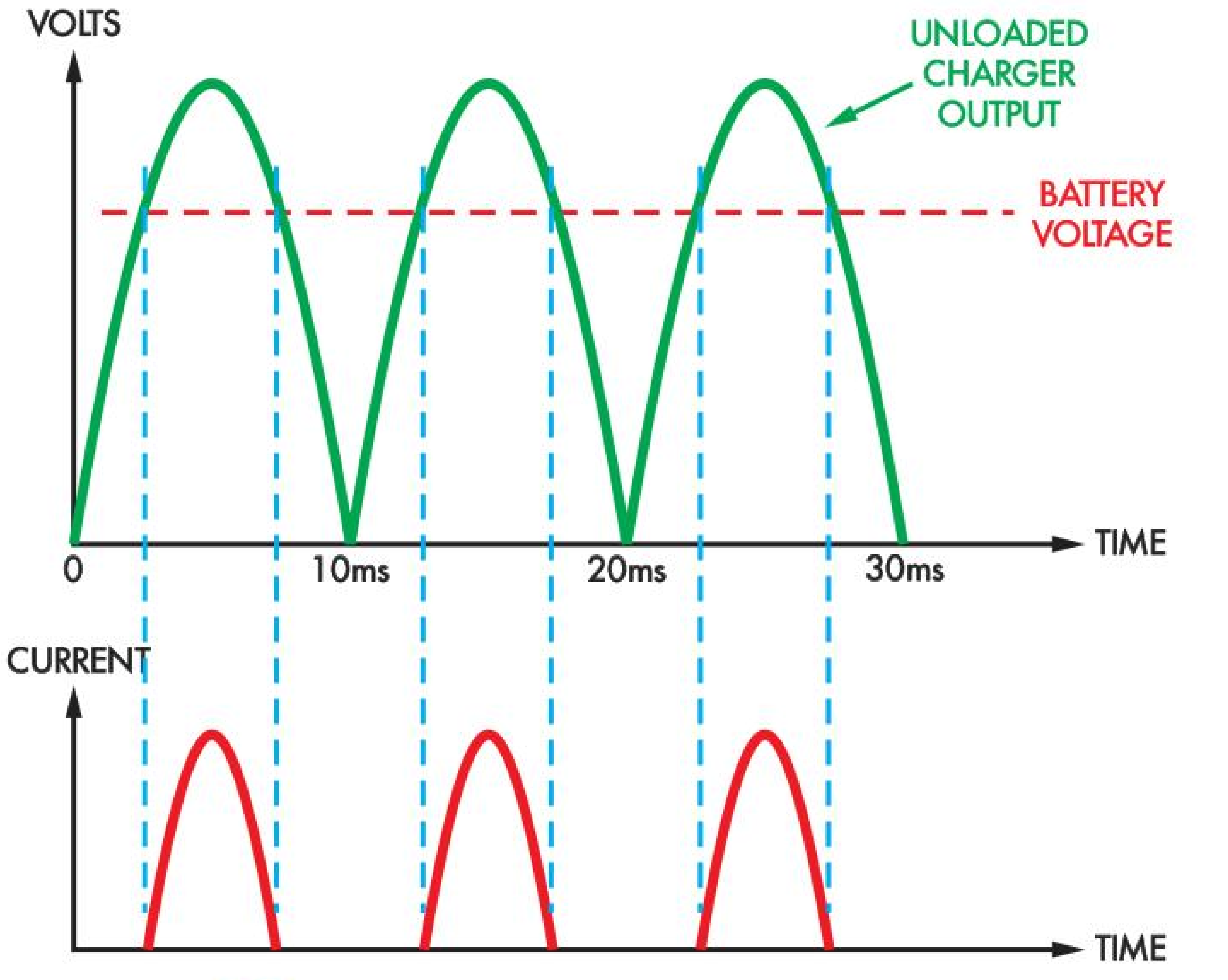
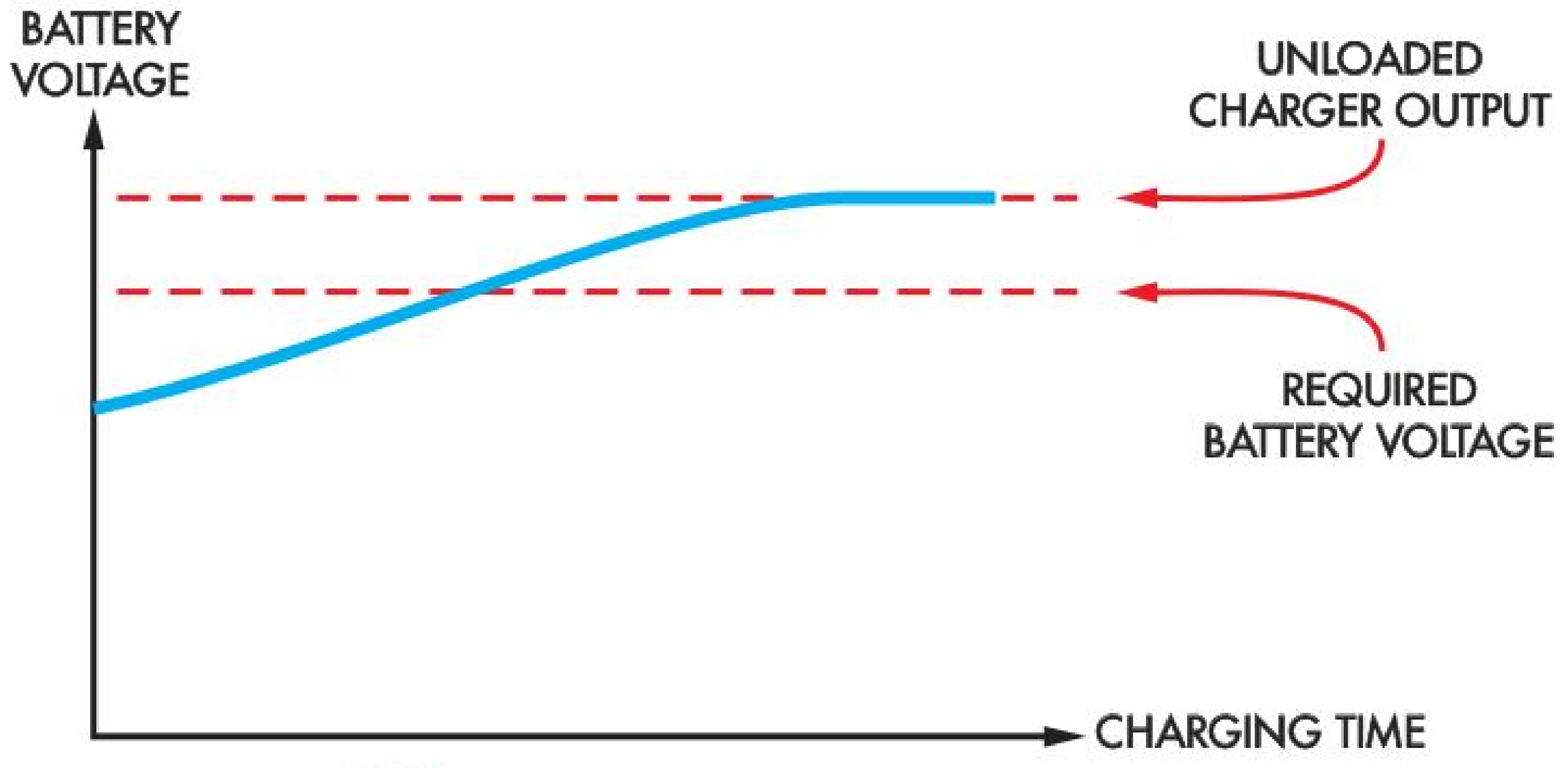


Fig.1: the basic arrangement of a typical low-cost lead-acid battery charger. It consists of a centre-tapped mains transformer and a full-wave rectifier (D1 and D2). There's usually a thermal cutout and perhaps an LED indicator to show when the battery is charged. The output voltage of this simple arrangement is shown above.



Ⓐ CHARGING VOLTAGE AND CURRENT



Ⓑ CHARGING CHARACTERISTIC

Fig.2. in more detail, the charging current from the circuit shown in Fig.1 consists of a series of high-current pulses at 100Hz. As shown in part (b), the relatively high peak voltage can result in the battery being over-charged if the charger is left on long enough.

rises. Some chargers may also have an ammeter to show the charging current.

The charging current to the battery is a series of high-current pulses at 100Hz, as shown in Fig.2(a). The nominal 17V peak output from the charger will eventually charge a battery to over 16V if left connected long enough, which will damage the battery. As shown in Fig.2(b), the maximum battery voltage for a full charge (called the cut-off voltage) is exceeded when left on charge for too long.

The solution

By adding in the *Charge Controller* to that simple charger, we can do much better. Fig.3 shows how the *Charge Controller* is connected in between the charger and the battery. The *Charge Controller* is housed in a compact diecast aluminium case. In effect, the *Charge Controller* is a switching device that can connect and disconnect the charger to the battery. This allows it to take control over charging and to cease charging when the correct voltage is reached.

The various charging phases for lead-acid batteries are shown in Fig.4. The *Charge Controller* can switch the current on or off and apply it in a series of bursts, ranging from 20ms every two seconds through to a continuous current.

During the first phase, called 'bulk charge', current is typically applied continuously to charge as fast as possible.

After the bulk charge phase, the *Charge Controller* switches to the 'absorption phase'. This maintains the cut-off voltage for an hour by adjusting the burst width while it brings the battery up to an almost full charge. After that, the *Charge Controller* switches to 'float charge'. This uses a lower cut-off voltage and a low charge rate, to keep the battery fully charged.

Features

- *Charges 6V, 12V or 24V flooded lead-acid, SLA or LiFePO$_4$ batteries at up to 10A (with a suitable charger)*
- *Charge rate: adjustable from 1-100% of charger capability in 1% steps*
- *One, two or three charging phases: bulk, absorption and float*
- *Adjustable or pre-set charge termination and float voltages*
- *Adjustable temperature compensation for lead-acid batteries with an internal or external thermistor*
- *Automatic slow charge mode for batteries that are heavily discharged*
- *Battery discharge protection*
- *Cold battery charge protection (won't charge below 1°C)*
- *Thermistor fault protection (won't charge lead-acid batteries if the thermistor is open or short circuit)*
- *Six status indicator LEDs with error indication*
- *Low-cost, easy to build and easy to use*
- *Microprocessor controlled*

The switch from absorption to float occurs when the charging current drops to 3% of the original bulk charge rate or after an hour, whichever comes first. The absorption phase is optional; you can choose to skip this phase and go straight from bulk charging to float charging.

When absorption is enabled, this phase will be bypassed if the bulk charge takes less than an hour. This prevents excessive absorption phase charging with an already fully charged battery.

While the bulk phase is usually done at the full rate, for lower capacity batteries where this charging current would be too high, the burst width can be reduced to limit the average current.

For example, if you have a 4A battery charger, the current can be reduced from 4A anywhere down to 40mA in 1% steps, using the charge rate control.

Lithium-iron-phosphate battery charging

Typically, LiFePO$_4$ batteries are charged to 3.47V per cell, although 3.6V per cell is also used. A nominally 12V LiFePO$_4$ battery therefore has four cells, and the cut-off voltage is either 13.88V or 14.4V, depending on which per-cell figure you use.

The *Charge Controller* can cease charging once the cut-off voltage is reached, or you can opt for an absorption phase. During this phase, the cut-off voltage is maintained for an hour, or until charging pulses drop to 3% of the original bulk charge setting.

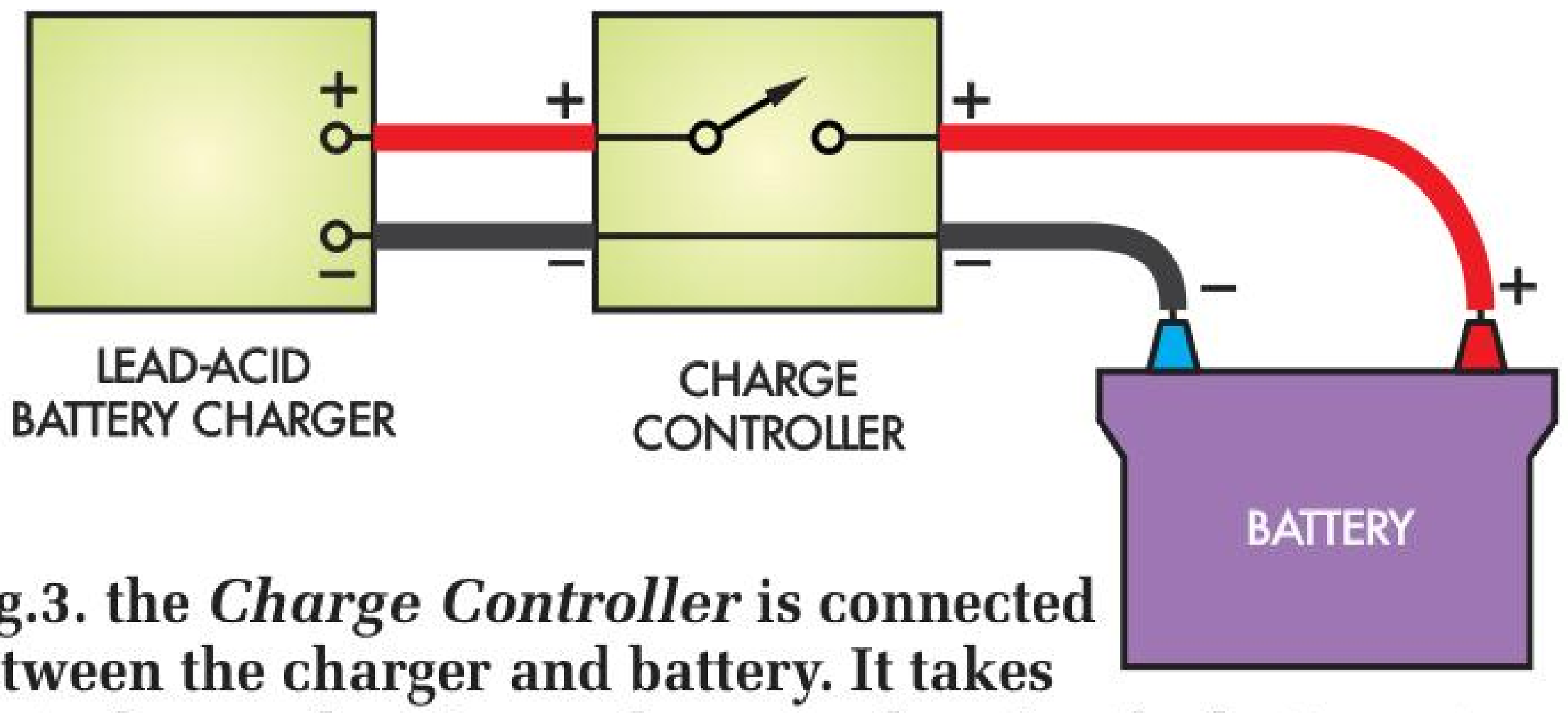


Fig.3. the *Charge Controller* is connected between the charger and battery. It takes control over charging and ceases charging the battery at the correct voltage; ie, when it is fully charged but before it becomes over-charged and starts out-gassing (or worse).

Specifications

- *Charging pulse width: 20ms-1980ms in 20ms steps, or continuous*
- *Charging cut-off voltage: 0-30.5V in 29.8mV steps. Independent LiFePO$_4$, SLA and lead-acid battery settings (presets are also available, see Table 1)*
- *Temperature compensation: 0-50mV/°C in 256 steps (separate SLA and lead-acid battery adjustments)*
- *Minimum battery charging temperature: 1°C*
- *Maximum compensation temperature: 60°C*
- *Under-voltage burst charge: 5.25V for a 6V battery, 10.5V for a 12V battery, 21V for a 24V battery*
- *Under-voltage burst rate: 200ms burst every 2s at maximum charge rate. The burst width is reduced with a lower charge rate (10% of the normal rate).*
- *Battery discharge protection: if charger power is lost, it switches off after two hours with battery voltage below 6.25V (for a 6V battery), 12.5V (for a 12V battery) or 25V (for a 24V battery)*
- *Power on: LED1 lights*
- *Thermistor error: LED2 lights*
- *Temperature too low: LED2 flashes at 1Hz*
- *Bulk charging: LED3 lights*
- *Absorption charging: LED4 lights; optionally, LED3 flashes to indicate charge rate*
- *Float charging: LED5 lights; optionally, LED3 flashes to indicate charge rate*
- *Battery detected: LED6 lights*
- *Battery voltage low, charging slowly: LED3 flashes; if charging a lead-acid battery, LED4 and LED5 also flash*

Lead-acid cut-off and float voltages

The actual cut-off and float voltages for lead-acid batteries are dependent on the particular battery, its construction and the operating temperature. Typical cut-off and float voltages at 20°C are 14.4V and 13.8V, respectively. For sealed lead-acid (SLA) batteries, the voltages are lower at 14.1V and 13.5V respectively.

These values, plus 13.88V for the LiFePO$_4$ battery, are pre-set within the *Charge Controller* and selected using the Lead-Acid/SLA/Lithium jumper shunts, but only when the 'default' shunt is inserted (not 'adjustable'). See Table 1.

Other settings are possible, and can be set manually from 0-30.5V in 29.8mV steps – see Table 2.

These voltage settings can also be compensated for temperature changes; as the temperature rises, the charge voltages for a lead-acid battery are normally reduced. A typical temperature compensation value is –20mV/°C for flooded cells and –25mV/°C for SLA batteries. LiFePO$_4$ batteries do not require temperature compensation.

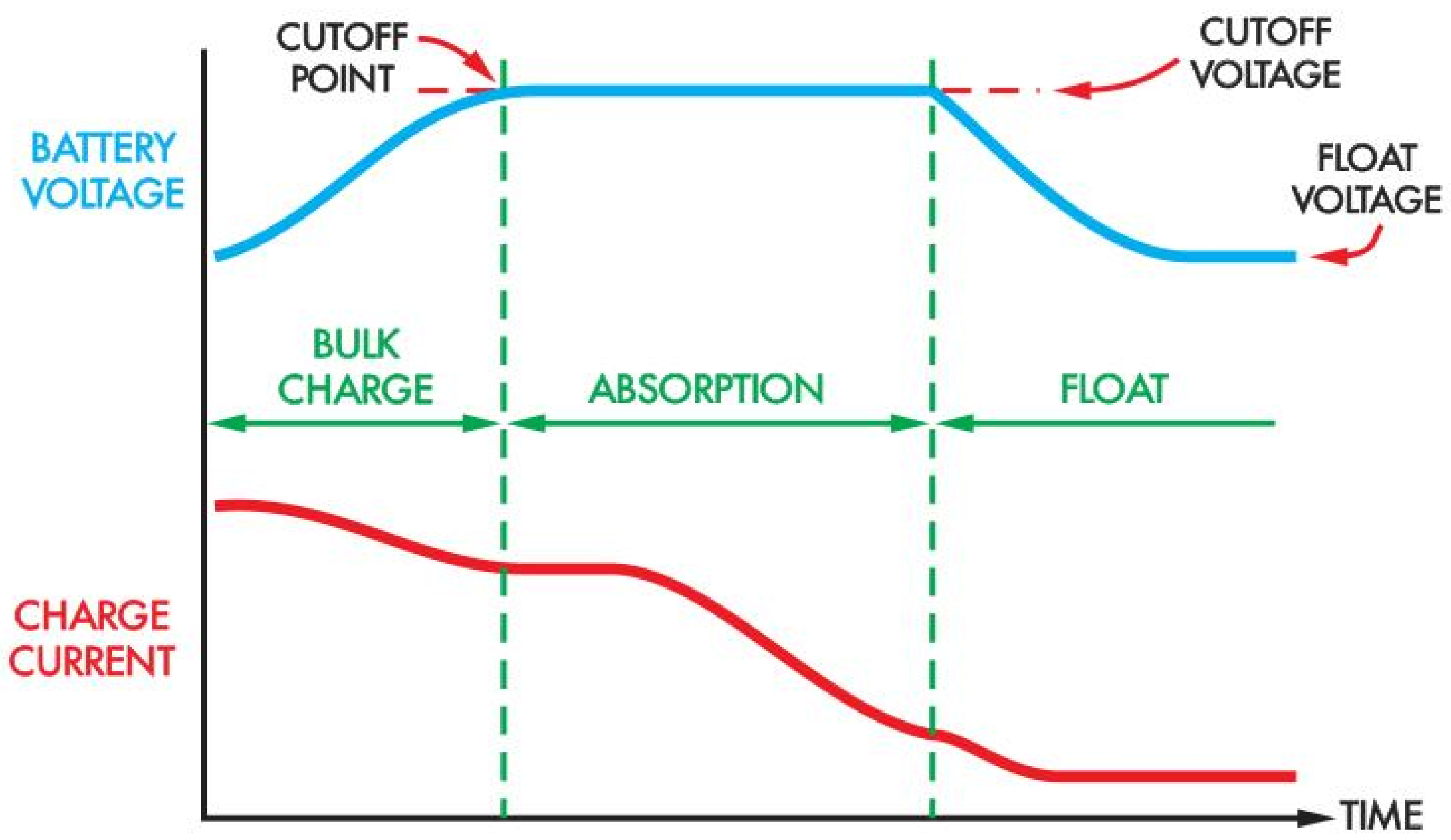


Fig.4: the three typical charging phases for a lead-acid battery. It starts with the bulk charge phase, then switches to the absorption phase (optional, selected using JP2) for an hour or so, and then finally switches to float charging to finish charging and keep the battery charged. For LiFePO$_4$ batteries, there is no float phase. The charger switches off when the battery is fully charged and switches back on again later if it becomes discharged.

Temperature compensation values can be set from between 0 to –50mV/°C in 256 steps. Temperature compensation is applied for temperatures between 0°C and 60°C. No charging is allowed at temperatures at or below 0°C, to protect the battery.

A negative temperature coefficient (NTC) thermistor is used for temperature measurement, and the *Charge Controller* will use the internal thermistor if an external one is not connected via its jack socket. The external thermistor provides for a more accurate measurement when it is placed against the battery.

Four trimpots are used to make the settings. One sets the charge rate, as a percentage of the full charge current available from the charger. The remaining three are for setting the cut-off voltage, float voltage and temperature compensation adjustments.

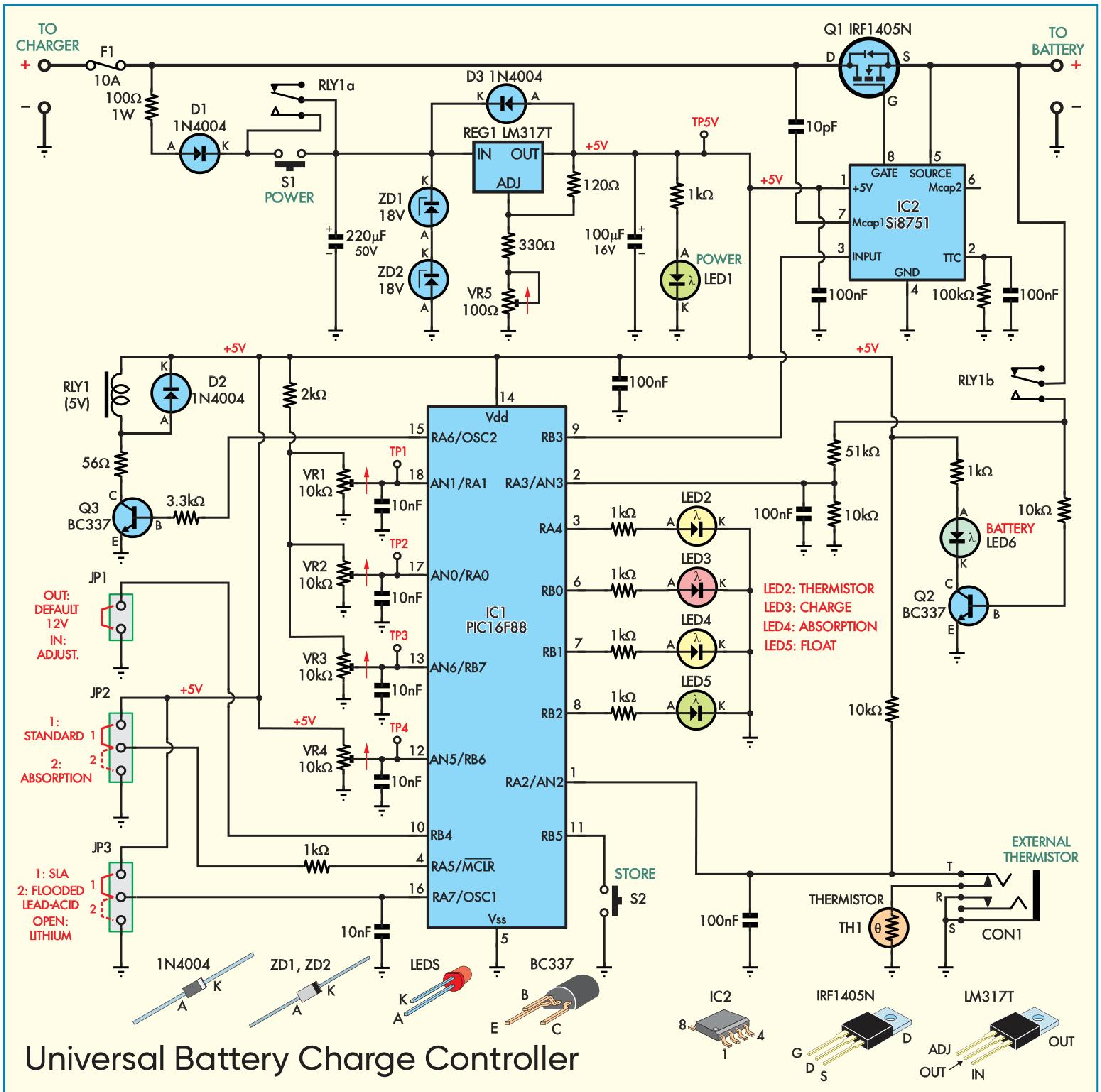
When charging the battery, the microcontroller adjusts the pulse duty cycle to reach the desired battery terminal voltage using negative feedback.

Setting	SLA	Flooded lead-acid	LiFePO$_4$
Cut-off voltage	14.1V	14.4V	13.88V
Float voltage	13.5V	13.8V	None
Temperature compensation	-25mV/°C	-20mV/°C	None

Table 1 – default settings

Setting	Set by	SLA and Flooded lead-acid	LiFePO$_4$
Cut-off voltage	VR2	0-30.5V*	0-30.5V*
Float voltage	VR3	0-30.5V*	None
Temperature compensation	VR4	0 to -50mV/°C	None

Table 2 – adjustable settings *in 29.8mV steps


TO CHARGER
+
–
F1
10A
100Ω
1W
D1
1N4004
A
K
RLY1a
S1
POWER
220µF
50V
D3 1N4004
REG1 LM317T
IN
OUT
ADJ
ZD1
18V
ZD2
18V
330Ω
VR5
100Ω
120Ω
+5V
100µF
16V
TP5V
1kΩ
POWER
LED1
Q1 IRF1405N
D
S
G
10pF
TO BATTERY
IC2
Si8751
GATE
SOURCE
+5V
Mcap2
Mcap1
INPUT
TTC
GND
100nF
100kΩ
100nF
RLY1
(5V)
D2
1N4004
56Ω
Q3
BC337
3.3kΩ
2kΩ
100nF
14
Vdd
15
RA6/OSC2
RB3
9
TP1
18
AN1/RA1
RA3/AN3
2
VR1
10kΩ
10nF
TP2
17
AN0/RA0
VR2
10kΩ
IC1
PIC16F88
TP3
13
AN6/RB7
VR3
10kΩ
TP4
12
AN5/RB6
VR4
10kΩ
10
RB4
4
RA5/MCLR
16
RA7/OSC1
Vss
5
RA4
3
RB0
6
RB1
7
RB2
8
RA2/AN2
1
RB5
11
LED2
LED3
LED4
LED5
LED2: THERMISTOR
LED3: CHARGE
LED4: ABSORPTION
LED5: FLOAT
51kΩ
10kΩ
100nF
RLY1b
1kΩ
BATTERY
LED6
Q2
BC337
10kΩ
10kΩ
JP1
OUT: DEFAULT 12V
IN: ADJUST.
JP2
1: STANDARD
2: ABSORPTION
JP3
1: SLA
2: FLOODED LEAD-ACID
OPEN: LITHIUM
1kΩ
10nF
STORE
S2
100nF
THERMISTOR
TH1
EXTERNAL THERMISTOR
T
R
S
CON1
1N4004
ZD1, ZD2
LEDS
BC337
IC2
IRF1405N
LM317T
OUT
ADJ
IN

Universal Battery Charge Controller

Fig.5: the *Charge Controller* circuit is based around a PIC16F88 microcontroller (IC1). This monitors the battery voltage at its AN3 input and switches MOSFET Q1 on and off via isolated driver IC2, to control the charging.

The duty cycle is reduced by 15% every two seconds if the battery voltage is above the required value by more than 0.25V, or reduced by 1% every two seconds if the battery voltage is above the required value by less than 0.25V.

Conversely, the charge duty cycle is increased at a fast rate (3% per two seconds) if the battery voltage is more than 0.25V below the required value and increased at a slow rate (1% per two seconds) if the battery voltage is low by less than 0.25V.

LED indicators

The *Charge Controller* has six LED indicators. LED1 (green) shows power is applied, while LED2 (orange) flashes when the thermistor temperature is below 0°C but otherwise does not light unless the thermistor connection is broken or shorted. LED3 (red) indicates the bulk charge phase, while LED4 (orange) and LED5 (green) indicate the absorption and float phases. LED6 (green) indicates that a battery is connected, but is not an indication that charging is occurring.

There is an option for LED3 to indicate when current is being fed to the battery during the absorption and float phases. This is useful, as it flashes whenever current is being fed to the battery.

So it indicates the duty cycle of power bursts. Brief bursts indicate that the battery is close to the required voltage, while longer bursts indicate that the battery requires further charging.

If this is not required, it can be disabled so that LED3 only lights during the bulk phase.

The absorption LED (LED4) will never light if you set up the charger to skip this phase. Similarly, the float LED (LED5) does not light when charging $LiFePO_4$ batteries, since that phase is not used for lithium batteries.

Isolated MOSFET drive

The circuit of the *Charge Controller* is shown in Fig.5. It uses a PIC16F88-I/P microcontroller (IC1) to monitor the battery voltage and adjust the switching of an N-channel

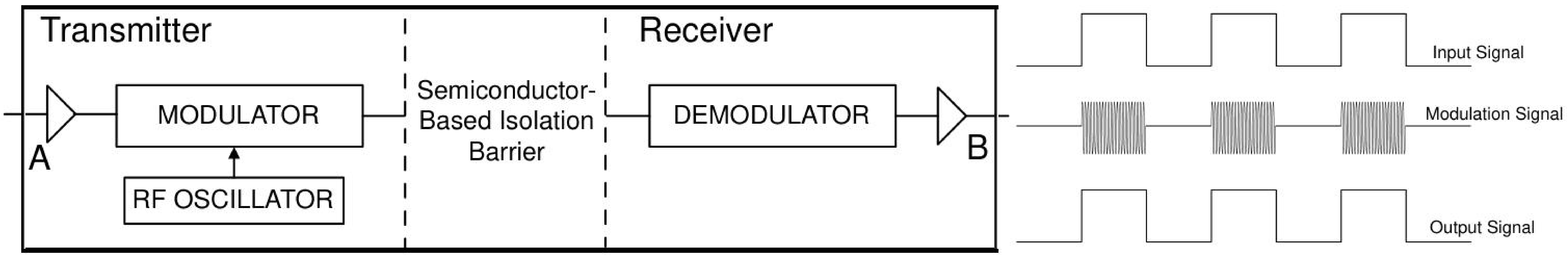


Fig. 6(a): Simplified Channel Diagram

Fig 6(b): Modulation Scheme

Fig.6: an excerpt from the Si8751 data sheet, showing its internal arrangement. It comprises an RF transmitter and RF receiver to transmit gate drive power and control from the input side to the output. The receiver is isolated from the transmitter by a semiconductor isolation barrier, rated at 2.5kV. When the RF transmitter is producing an RF signal, a gate-drive voltage appears at the output. When there is no RF transmission, there is no gate-drive voltage.

MOSFET (Q1) to control the charging rate. Q1's channel is connected between the incoming positive supply (drain) and the battery positive terminal (source).

To switch Q1 on, its gate needs to be brought several volts higher than its source. Since the source is at the battery voltage, we need a way to generate a voltage above this. This needs to be controlled by a 0-5V control signal from microcontroller IC1. To accomplish this, we use an Si8751 isolated FET driver (IC2). It provides up to 2.5kV of isolation between its input and output, but here, 45V is sufficient.

IC2 runs from the same 5V supply as microcontroller IC1, and Q1's gate is driven from pin 8. The MOSFET source is connected to pin 5. The gate drive output at pin 8 typically charges the gate to 10.8V with respect to the source when the input at pin 3 is high (5V). The gate output is pulled down to the source voltage with a 0V input.

The 10pF capacitor between drain and MCAP1 (pin 7) enables a feature of the chip to prevent a fast voltage rise at the MOSFET drain from coupling into its gate and spuriously switching it on.

Internally, IC2 comprises an RF transmitter and RF receiver to send gate drive power from the input side to the isolated output. Isolation is provided by a semiconductor oxide barrier. When the transmitter is producing an RF signal, this is detected in the receiver to produce the gate drive voltage. When there is no RF transmission, there is no gate drive. See Fig.6 for details of its internal operation.

The gate drive current is set by the resistor at pin 2. In combination with the MOSFET's gate capacitance, this determines the MOSFET switch-on time. With the 100kΩ resistor we've used, the switch-on time is around 5ms to a gate voltage of 5V. It continues to rise to about 10V, but the MOSFET is already mostly in conduction by 5V.

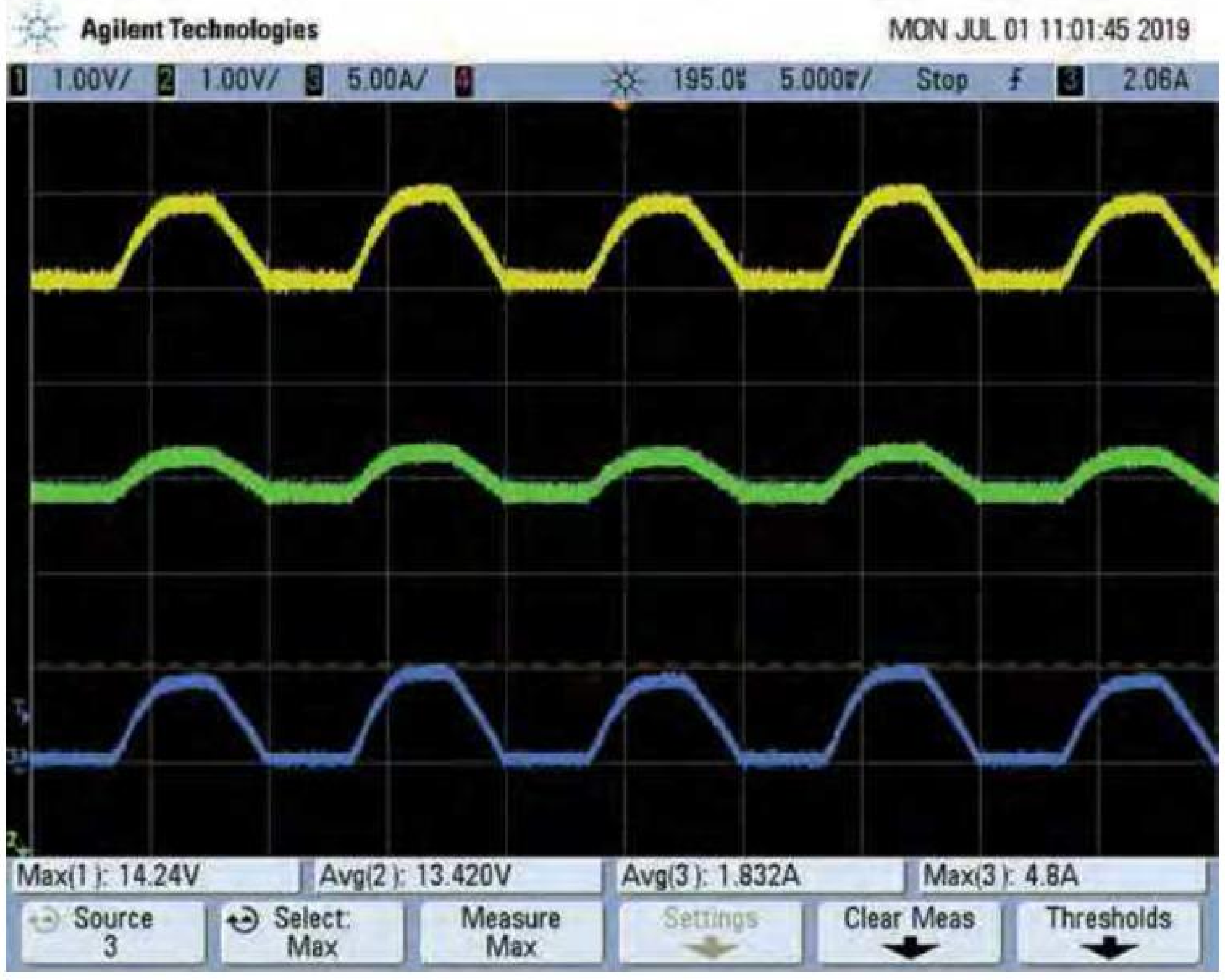
The 100kΩ resistance we have chosen reduces the supply current for IC2 from 13.8mA down to 1.8mA, compared to the fastest option of connecting pin 2 directly to ground, which would give a 1ms switch-on time. The 100nF capacitor across the 100kΩ resistor speeds up switch-on without increasing current consumption. The switch-off time is typically 15µs, regardless of the resistor value at pin 2.

Fast switching isn't required in this application, as we're only switching the MOSFET on/off once every two seconds.

Low current consumption is important, so that REG1's dissipation is below 1W when charging a 24V battery. Otherwise, the regulator will run very hot and need heatsinking beyond that provided by the PCB.

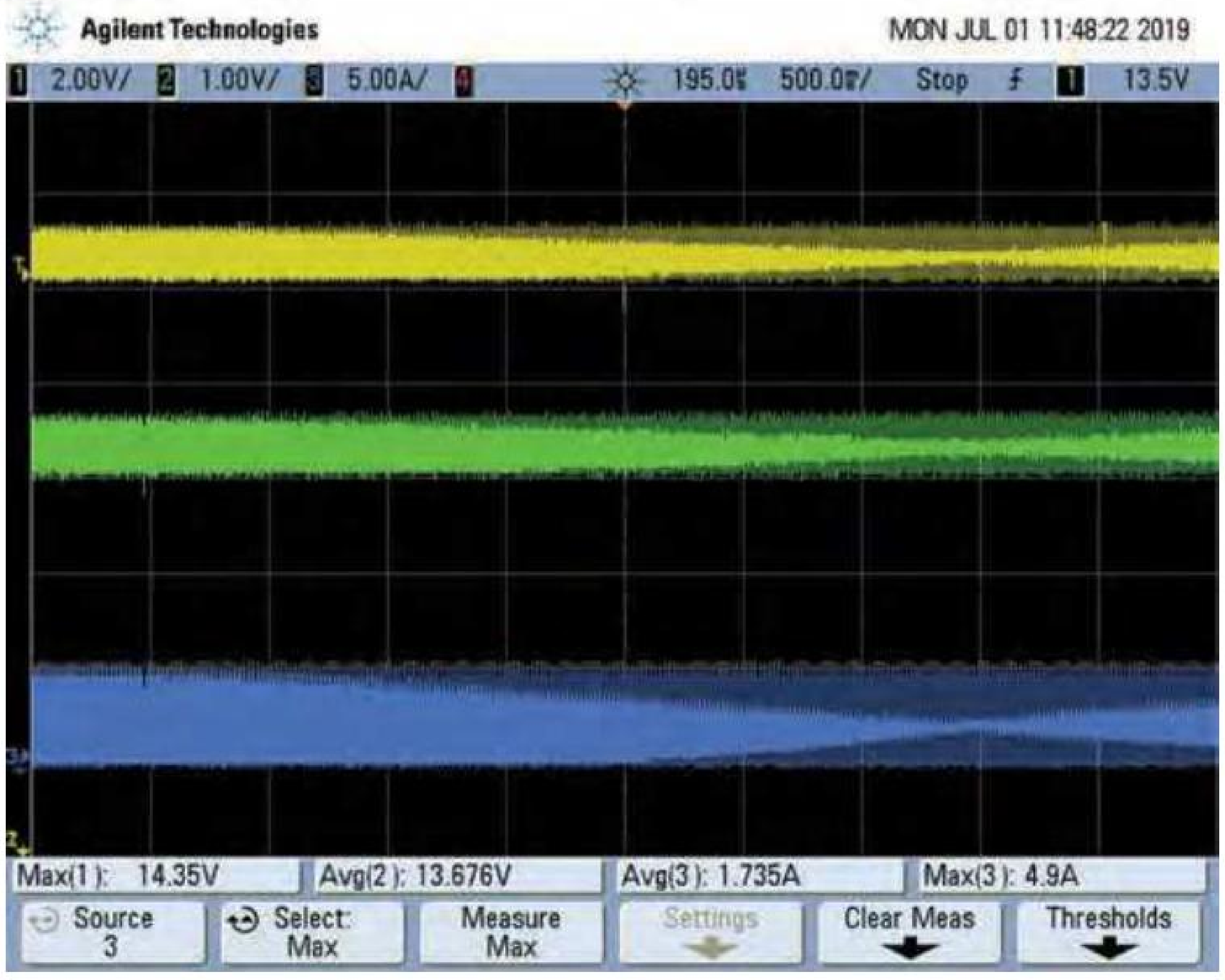
Switching losses increase when the switching is slow because the MOSFET's dissipation is at a maximum when it is in partial conduction. The instantaneous losses can be high (hundreds of watts at many amps), but as they are infrequent, the average is low. Switching losses are: (switch-on loss + switch-off loss) × switching frequency. So losses are directly proportional to frequency.

Fig.7 is an oscilloscope screen grab showing the gate drive waveform for MOSFET Q1. The period for the gate to rise from 0V, with the MOSFET off, to fully conducting (4.5V) is 5ms. The switch-off time is relatively fast at around 35µs for the full gate-voltage excursion.



Max(1): 14.24V
Avg(2): 13.420V
Avg(3): 1.832A
Max(3): 4.8A

Scope1: scope grab of the *Charge Controller* with a 2A charger and a lead-acid car battery. The yellow trace shows the charger output, the green trace the battery voltage and the blue trace the charge current. Note how the battery voltage varies with the charging current. The difference in voltage between the charger and the battery is due to the current shunt and cable losses.



Max(1): 14.35V
Avg(2): 13.676V
Avg(3): 1.735A
Max(3): 4.9A

Scope2: the same charging scenario as Scope1 but at a much longer timebase, showing the many pulses that make up two seconds of charging.

The overall energy loss in the MOSFET (and therefore heating) is the switching losses plus the static losses. We've already explained that the switching losses are reasonably low. The static losses are simply the average current times the MOSFET's on-resistance. Its on-resistance is low enough that even at 10A, the static losses are within reason.

Circuit description

Power for the circuit is usually obtained from the 'dumb' charger via reverse-polarity protection diode D1, although it can also flow from the battery via the body diode within Q1. However, the latter has no useful function and can eventually discharge the battery. We have a solution for that, which is described below.

The incoming supply also passes through a 100Ω dropper resistor and either power switch (pushbutton) S1 or the contacts of RLY1, and is then filtered by a 220µF electrolytic capacitor and fed to an LM317T adjustable regulator (REG1), set to deliver a precise 5.0V. For REG1, the voltage between the OUT and ADJ terminals is a fixed reference value of typically 1.25V, but it could be between 1.2 and 1.3V. Assuming it is 1.2V, the 120Ω resistor between these pins has 10mA (1.2V ÷ 120Ω) flowing through it, which also passes through the 330Ω resistor and trimpot VR5.

We need 3.8V at the ADJ terminal for a 5V output (3.8V + 1.2V), so the total resistance of VR5 and the 330Ω resistor needs to be 380Ω for the 10mA current to produce this voltage. VR5 is therefore adjusted to give 50Ω. This adjustment is provided to allow for variations in REG1's reference voltage and the resistor values.

The 5V supply feeds both IC1 and IC2. The accuracy of the 5V setting adjustment determines the precision of the battery-charge voltage settings. That is because IC1 uses the 5V supply as a voltage reference to compare the measured battery voltage against.

Preventing battery discharge

To switch the *Charge Controller* on, momentary pushbutton S1 is pressed, allowing current to flow into REG1. IC1 then switches on RLY1, shorting out S1 so that the circuit remains powered after it is released. RLY1 is controlled by digital output RA6 of IC1 (pin 15), which goes high to drive the base of NPN transistor Q3, energising the relay coil via a 56Ω resistor.

Using the Charge Controller with 6V batteries

The circuit as presented is suitable for use with 12V or 24V batteries and chargers, but it can easily be modified for 6V batteries and chargers with a few changes. Note that if you make these changes, you can only use the unit with a 6V charger.

The changes required are: replace D1 with a 1N5819 Schottky diode, change the 100Ω 1W resistor to 10Ω 1W and change REG1 to the low-dropout version, LD1117V. ZD1 should be changed to a 15V 1W type and ZD2 replaced with a wire link.

The default position for JP1 cannot be used with 6V batteries; set the adjustable cut-off voltage, float voltage and temperature compensation values to suit your particular 6V battery.

This resistor reduces the current through the relay coil, as the relay will operate down to 3.75V and so we save a little power this way. Without the resistor, the relay coil current is 28mA, and with it, it is 21mA.

The other set of contacts in RLY1 make the connection between the battery and the 51kΩ and 10kΩ battery-voltage-measuring resistors.

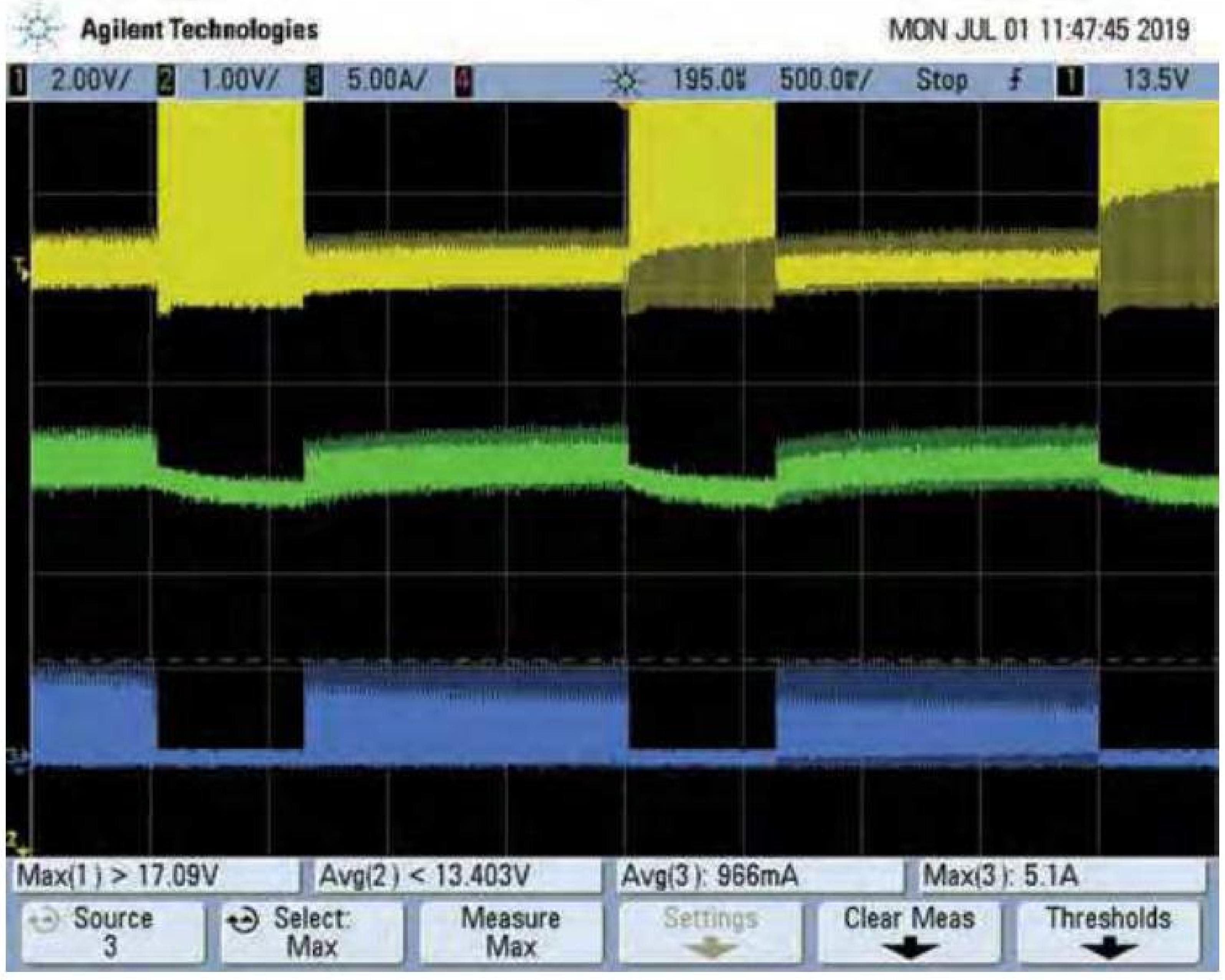
If the charger is switched off or a blackout occurs with the battery still connected, the battery powers the *Charge Controller* and it could become over-discharged and damaged if this continues long enough. With the charger power off, the circuit draws around 50mA from the battery.

To prevent this, IC1 monitors battery voltage and when the battery voltage falls below 12.5V for a 12V battery or 25V for a 24V battery for at least two hours, the RLY1 switches off. This totally removes the load from the battery, as current can no longer flow from it into REG1 or the voltage divider.

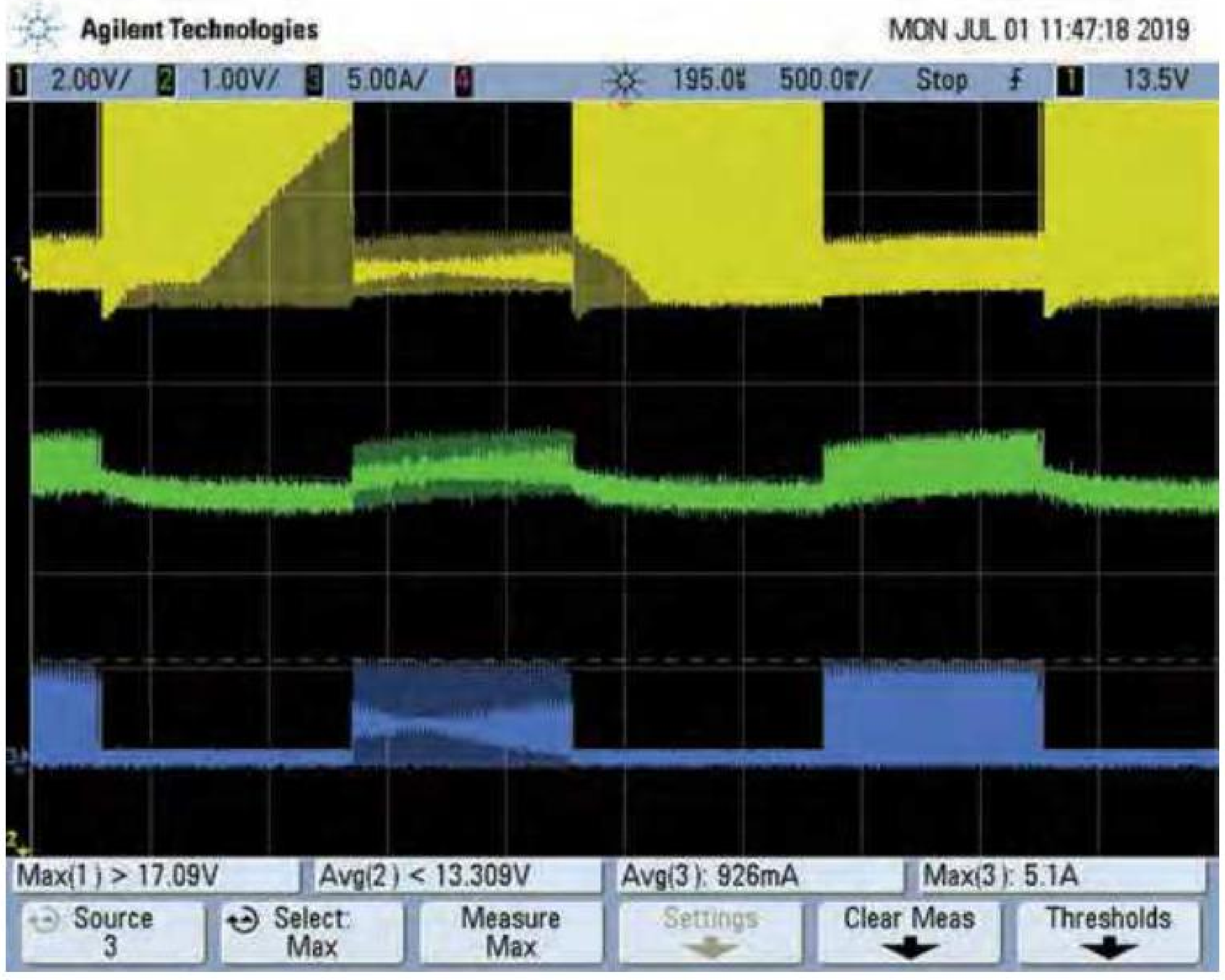
Battery voltage measurements

When the *Charge Controller* is powered up, the 51kΩ and 10kΩ resistors allow IC1 to monitor the battery voltage at its AN3 analogue input (pin 2). The resistors reduce the battery voltage to be within its 0-5V measurement range.

So, for example, if you have a 24V battery at its maximum standard charge voltage of 28.8V, the battery voltage is



Scope3: we have now reduced the charging duty cycle to around 75% and the average current delivered to the battery has dropped (the reading is unrealistically low due to the timing of the pulses). Note how the battery voltage rises during the bursts, then falls a little between them, averaging lower than before. The charger output voltage rises substantially when it is not delivering current.



Scope4: now the duty cycle has been reduced to 50% and the battery voltage and average charge current have dropped a little further.

Making a fully self-contained charger

While the emphasis in this project has been to make a dumb battery charger clever, we can already hear the question: ***What do you do if you don't have a dumb battery charger?*** *The answer to that is simple! There is absolutely nothing to stop you making one, as per Fig.1 in this article, and add it to the project. You won't need the LED/zener indicator (the Charge Controller tells you everything you need); the thermal cutout wouldn't do any harm, though.*

In fact, you could place a 12V CT transformer and a pair of diodes in a larger case and include this project to have a fully self contained, clever battery charger. If you can't lay your hands on a 12V CT transformer, a single-ended 12V with a bridge rectifier will do the same job. Just remember that the transformer (in either case) ***must be a standard iron-core type*** *(not an electronic type) rated high enough – we'd suggest 4A or 50W (did we hear someone say an old 12V downlight transformer?). And the diodes or bridge need to be pretty beefy, too – a pair of automotive diodes or a 30A bridge, for example.*

Make sure the mains wiring side is exemplary – in fact, all wiring must be workmanlike, properly anchored and so on. Any metal case should be properly earthed (via the power cord).

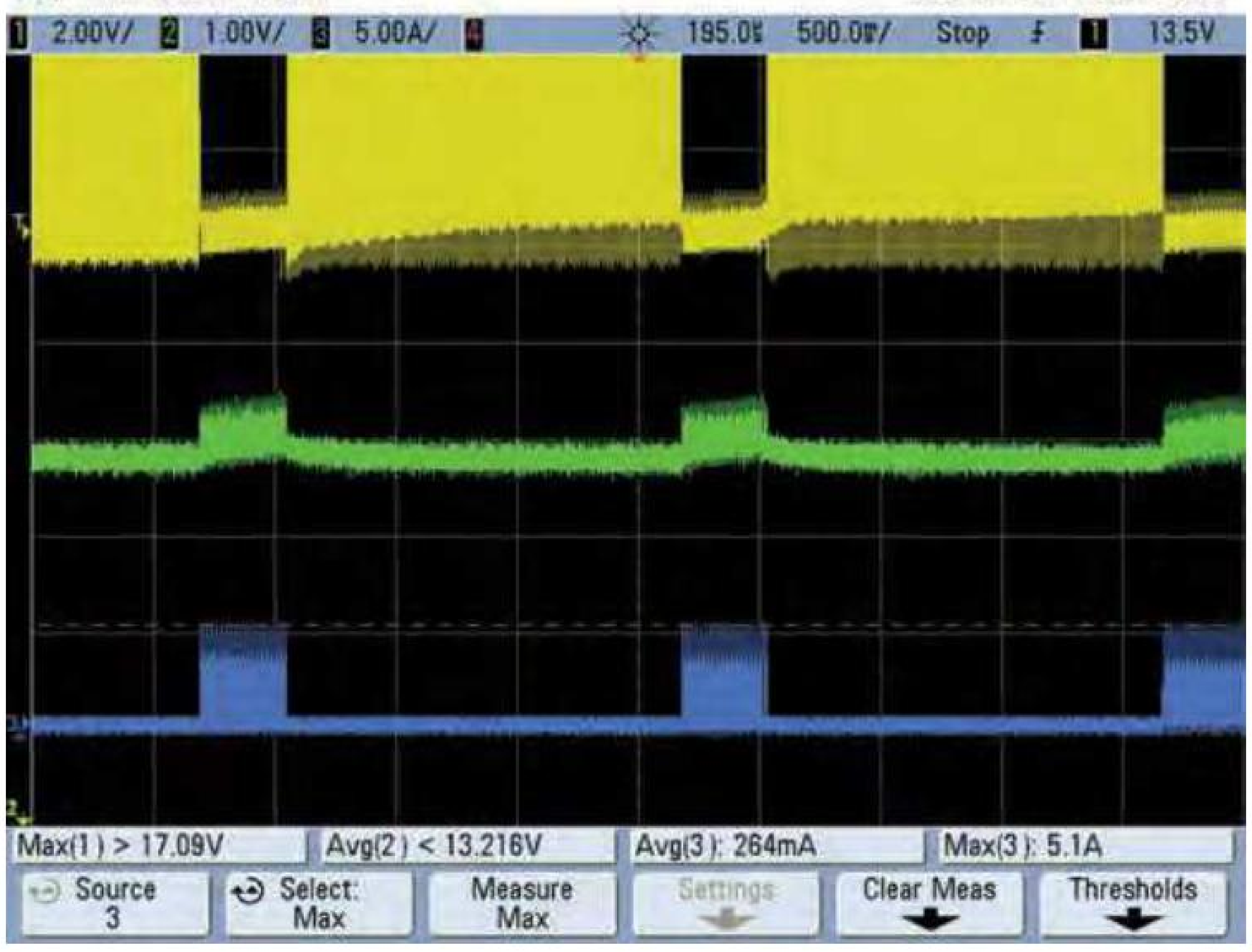
So away you go . . .

divided down by a factor of 6.1, giving 4.72V at pin 2 of IC1. The voltage is filtered with a 100nF capacitor to remove noise from the measurement. IC1 converts the voltage to a 10-bit digital value (0-1023), which gives a 29.8mV resolution (5V × 6.1 ÷ 1023). Battery voltage measurements are made when Q1 is switched off, so voltage fluctuations due to the charging current in the leads to the battery don't affect it.

Temperature measurement

An NTC thermistor is used to measure the battery temperature. One thermistor mounts on the PCB and connects to pin 1 of micro IC1 via the switched tip contact of 3.5mm jack socket CON1. When an external thermistor is connected via CON1, the internal thermistor is switched out and the external thermistor connects to pin 1 of IC1 instead.

Note that the external thermistor is connected to ground via the ring connection. The sleeve is left open. This allows the metal enclosure of the *Charge Controller* to remain floating from the controller circuit.



Scope5: the duty cycle has now been reduced to 10% but the battery is still charging (slowly), with an average terminal voltage of 13.2V.

In either case, the thermistor is connected in series with a 10kΩ resistor across the 5V supply. It therefore forms a voltage divider and the resulting voltage, which is related to the thermistor temperature, appears at the AN2 input (pin 1) of IC1 and is converted to an 8-bit digital value. IC1 then uses a look-up table to convert the voltage to a temperature value, as the relationship is non-linear.

IC1 can sense whether the thermistor is disconnected; eg, if the wire to the external thermistor is broken. Pin 1 would then be at +5V. Similarly, if the resistor is shorted to ground, IC1 can detect this as pin 1 will be at 0V. The thermistor LED lights in either case, and charging ceases.

The thermistor LED flashes when the measured temperature is 0°C or below. Charging also ceases in this case.

Set-up adjustments

Analogue inputs AN5, AN6, AN0 and AN1 (pins 12, 13, 17 and 18) are used to monitor the settings for charge rate percentage, cut-off voltage, float voltage and temperature compensation, as set with trimpots VR1 to VR4.

Switch S2 is pressed to store the settings in IC1's Flash. S2 is normally open, and an internal pull-up resistor within IC1 holds the RB5 input (pin 11) at 5V. When S2 is pressed, the pin 11 input is pulled low (to 0V) and this signals the program within IC1 to store the settings for VR2, VR3 and VR4 as the adjustable values for either SLA, lead-acid or lithium batteries.

These values are only stored if the jumper JP1 is in the 'adjustable' position. Where the values are stored depends on the position of the battery chemistry selection jumper JP3. This is monitored by IC1's RA7 digital input (pin 16).

Jumper link JP1 sets whether the *Charge Controller* uses the standard (or default) values or the adjustable settings referred to above.

JP2 selects the absorption option. If this jumper is not in the 'absorption' position, when charging lead-acid batteries, the charger switches to float charging as soon as bulk charging is complete. For $LiFePO_4$ batteries, in this position, charging ceases as soon as the bulk charge is complete.

If absorption charging is enabled by JP2, the absorption phase will run after the bulk charge, provided that the charging process has been going for more than one hour. At the end of the absorption phase, the unit either switches to float charging (for lead-acid) or ceases (for $LiFePO_4$).

Since the battery chemistry selection jumper (JP3) can have three possible states, including 'open', there is a 10nF

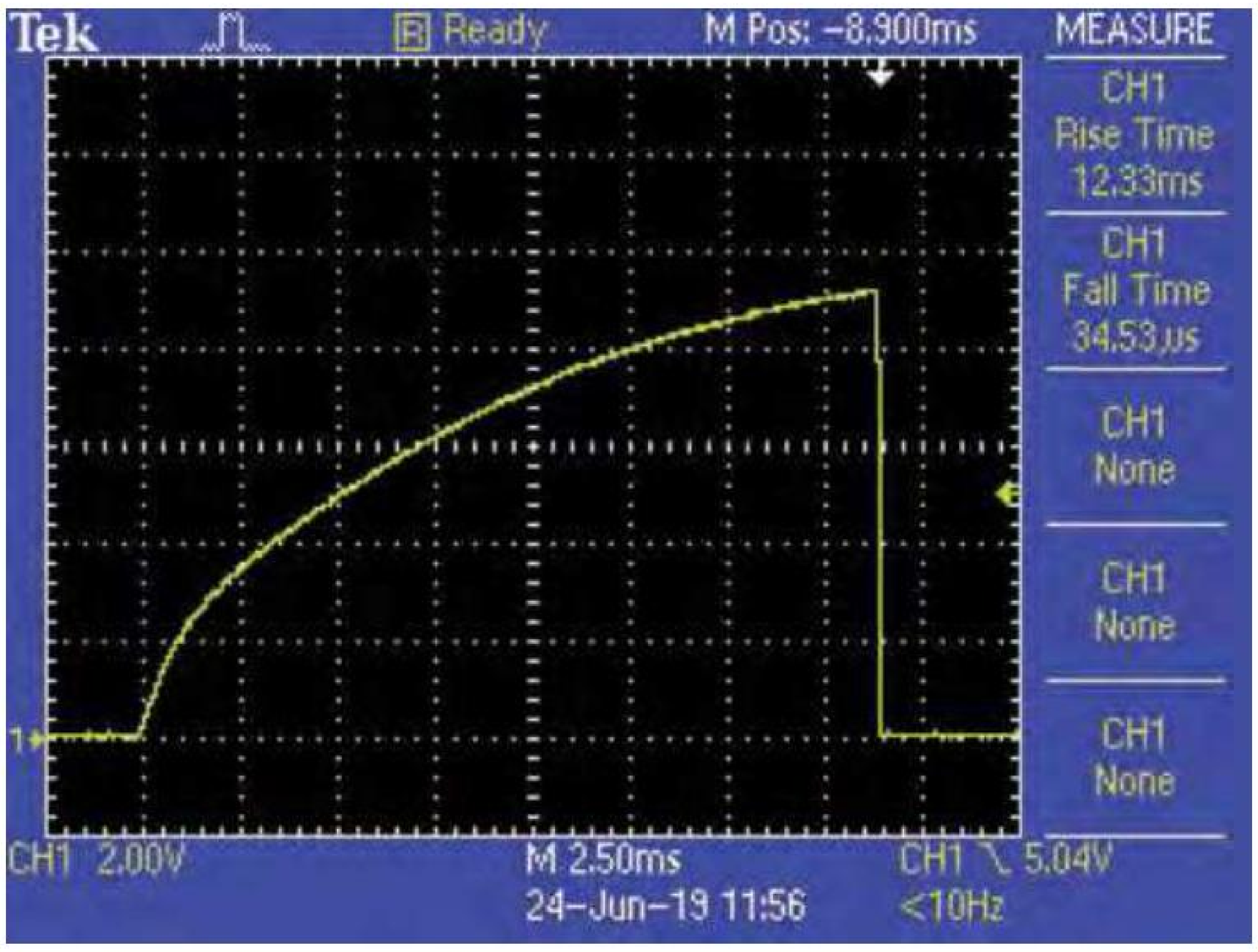


Fig.7: this scope grab shows the voltage at the gate of Q1 for a single, short pulse. The vertical scale is 2V/div and the horizontal scale is 2.5ms/div. The MOSFET switches on at around 4-5V, so we can determine from this that the switch-on time is around 5ms, while the switch-off time is much shorter, les than 0.1ms (100µs).

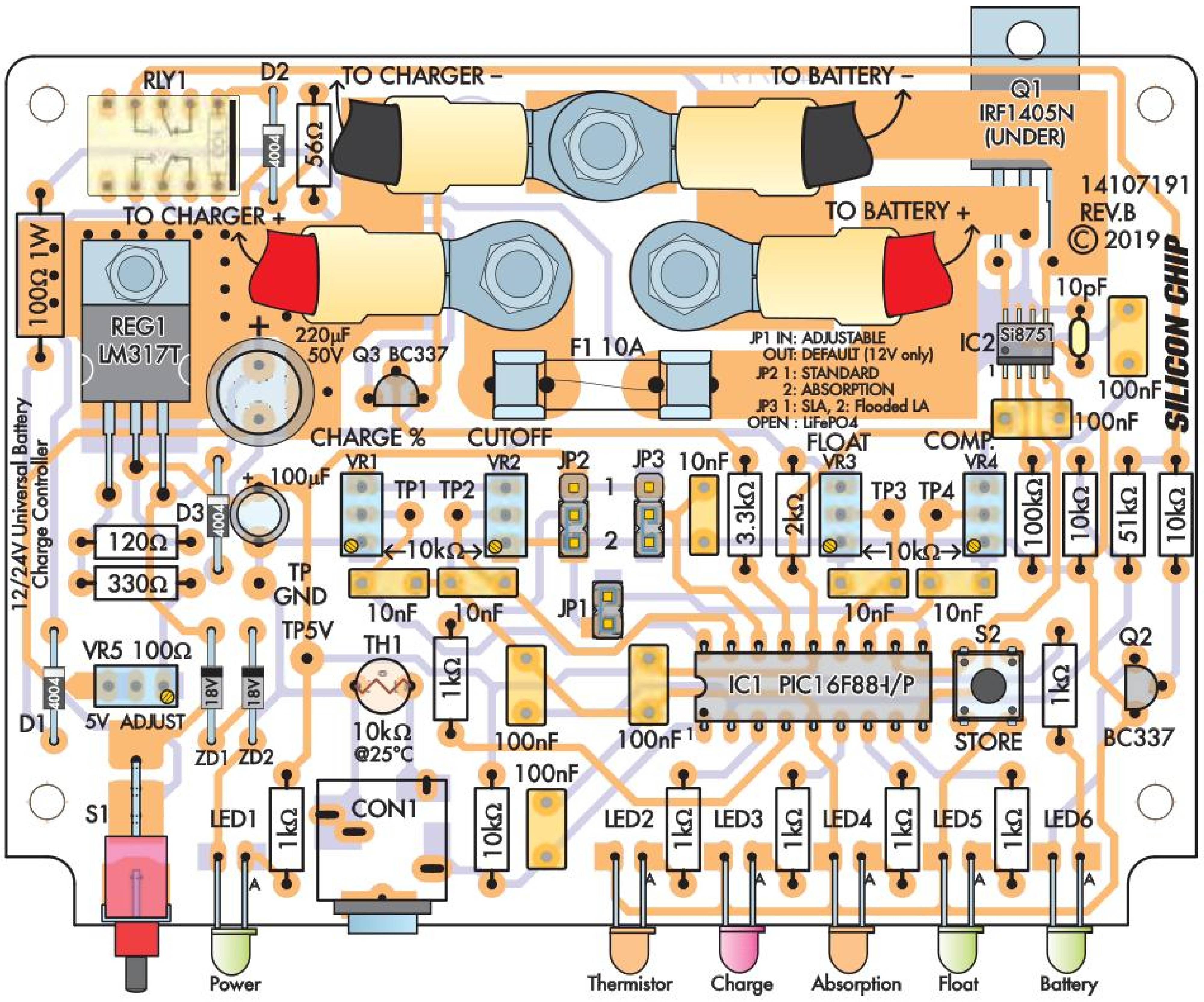
capacitor connected from pin 16 of IC1 to ground. IC1 can therefore briefly pull this pin high or low, then cease driving it and sample the voltage at it.

If no jumper is inserted, the voltage will be as expected, but if a jumper is in place, it will prevent the capacitor from charging or discharging.

Indicator LED driving

Power indicator LED1 runs from the 5V supply via a 1kΩ current-limiting resistor. LED2, LED3, LED4 and LED5 are driven from the RA4, RB0, RB1 and RB2 digital outputs of IC1 (pins 3 and 6-8), via 1kΩ resistors.

LED6 is the battery detection indicator and is driven via transistor Q2 via a 1kΩ resistor from the 5V supply. The base of this transistor connects to the switched side of RLY1's second set of contacts via a 10kΩ resistor. This transistor switches on when battery voltage is present. This prevents the LED brightness from varying significantly between different battery types.


RLY1
D2
TO CHARGER –
TO BATTERY –
Q1
IRF1405N
(UNDER)
14107191
REV.B
© 2019
TO CHARGER +
TO BATTERY +
100Ω 1W
REG1
LM317T
220µF
50V
Q3 BC337
F1 10A
JP1 IN: ADJUSTABLE
OUT: DEFAULT (12V only)
JP2 1: STANDARD
2: ABSORPTION
JP3 1: SLA, 2: Flooded LA
OPEN : LiFePO4
IC2
Si8751
10pF
100nF
SILICON CHIP
12/24V Universal Battery Charge Controller
CHARGE %
CUTOFF
FLOAT
COMP.
VR1
VR2
VR3
VR4
JP2
JP3
10nF
100µF
TP1
TP2
TP3
TP4
3.3kΩ
2kΩ
100kΩ
10kΩ
51kΩ
D3
120Ω
330Ω
TP GND
TP5V
JP1
VR5 100Ω
5V ADJUST
TH1
10kΩ @25°C
1kΩ
IC1 PIC16F88-I/P
S2
STORE
Q2
BC337
D1
ZD1
ZD2
18V
S1
LED1
CON1
LED2
LED3
LED4
LED5
LED6
A
Power
Thermistor
Charge
Absorption
Float
Battery

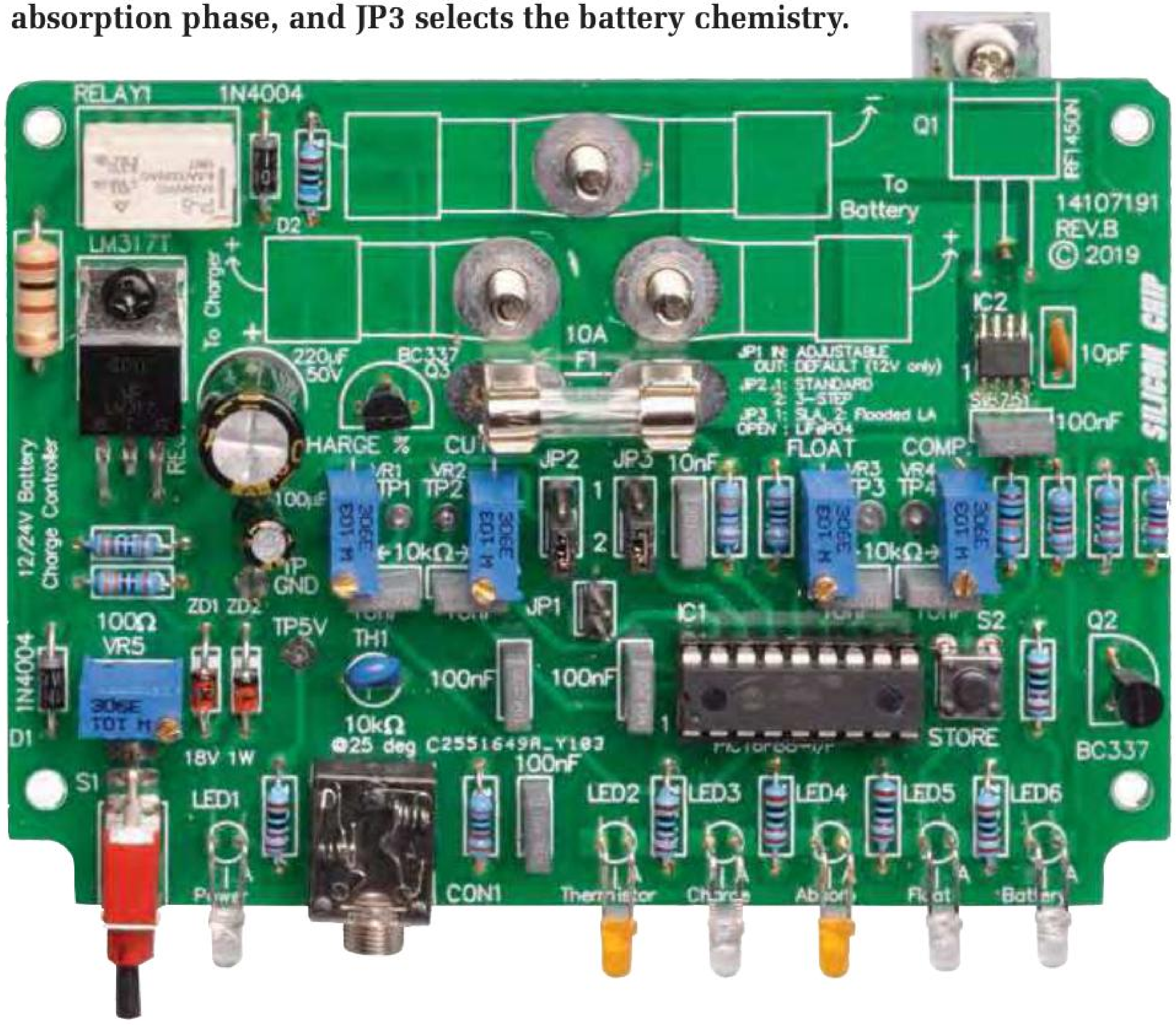


Fig.8: fit the parts to the PCB as shown above and the photo below. Watch the orientation of the diodes, ICs, LEDs, trimpots and relay. Note that the LEDs should be fitted at right-angles, as shown here, to project through the side of the case. Q1 is fitted last as it's attached to the bottom of the case before soldering its leads on the top side of the board. Jumper JP1 selects between default or adjustable charging parameters, JP2 enables or disables the absorption phase, and JP3 selects the battery chemistry.

Construction

The *Charge Controller* is built on a PCB coded 14107191, measuring 111 × 81mm and available from the *PE PCB Service*. This is housed in a 118 × 93 × 35mm diecast aluminium box.

It's best to start by preparing the box. This way, you can use the blank PCB as a template. First, locate the PCB in the bottom of the box with the edge closest to the LEDs against that edge of the box. Mark out the four corner mounting hole positions, then drill these holes to 3mm and deburr them.

Copy the panel artwork (Fig.8) and use it as a template to drill out the holes in the front of the enclosure for the switch, 3.5mm socket and LEDs. Make sure the template is lined up with your PCB mounting location before drilling the holes.

The power switch hole is 4.5mm in diameter (5mm is OK) and the thermistor socket is 6.5mm (7mm is OK). The other panel holes are 3mm.

You can now start assembling the PCB. Fig.8 shows the overlay diagram, which you can use as a guide during construction.

Start by fitting IC2. This is an 8-pin surface mount device that's relatively easy to solder using a fine-tipped soldering iron. The pin 1 location is marked with a small dot on the package. Line the IC up on the PCB pads and tack-solder one of the corner pins. Check that the IC is still aligned correctly on all the pads. If not, re-heat the solder and adjust again.

When aligned correctly, solder all the pins including the original tack-soldered pin. If any pins are bridged together, use flux paste and solder wick to clear the bridge.

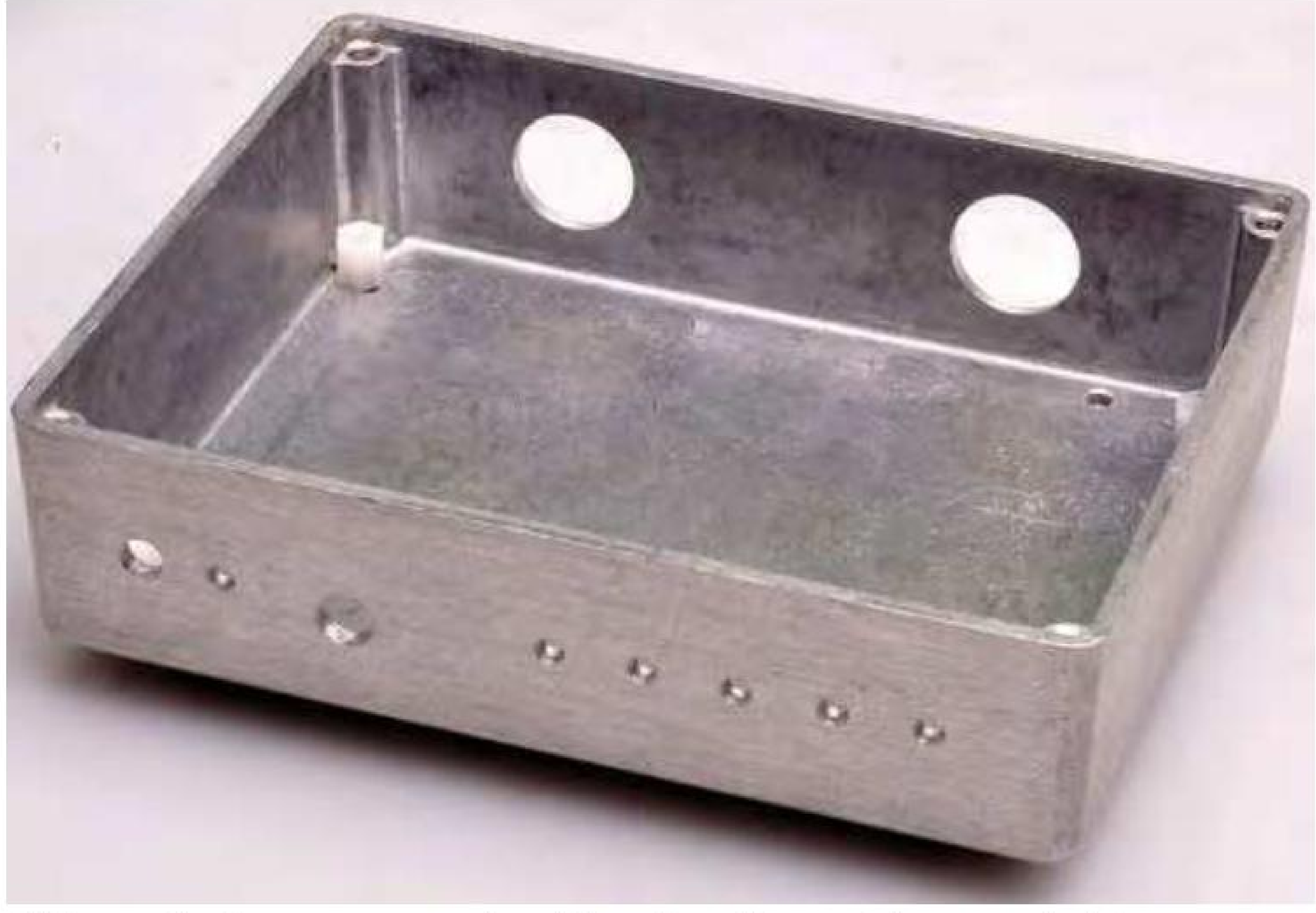
Next, insert the three M4 screws from the underside of the PCB at each of the eyelet mounting positions and secure using M4 nuts on the top of the PCB. Using a soldering iron, preheat each screw and solder it to the board. Make sure the solder adheres to each screw head. When cool, the nuts can be removed.

Note that you may be able to build the unit without having to solder the screw heads if you use M4 copper crinkle washers under each screw head instead, but they are not that easy to find.

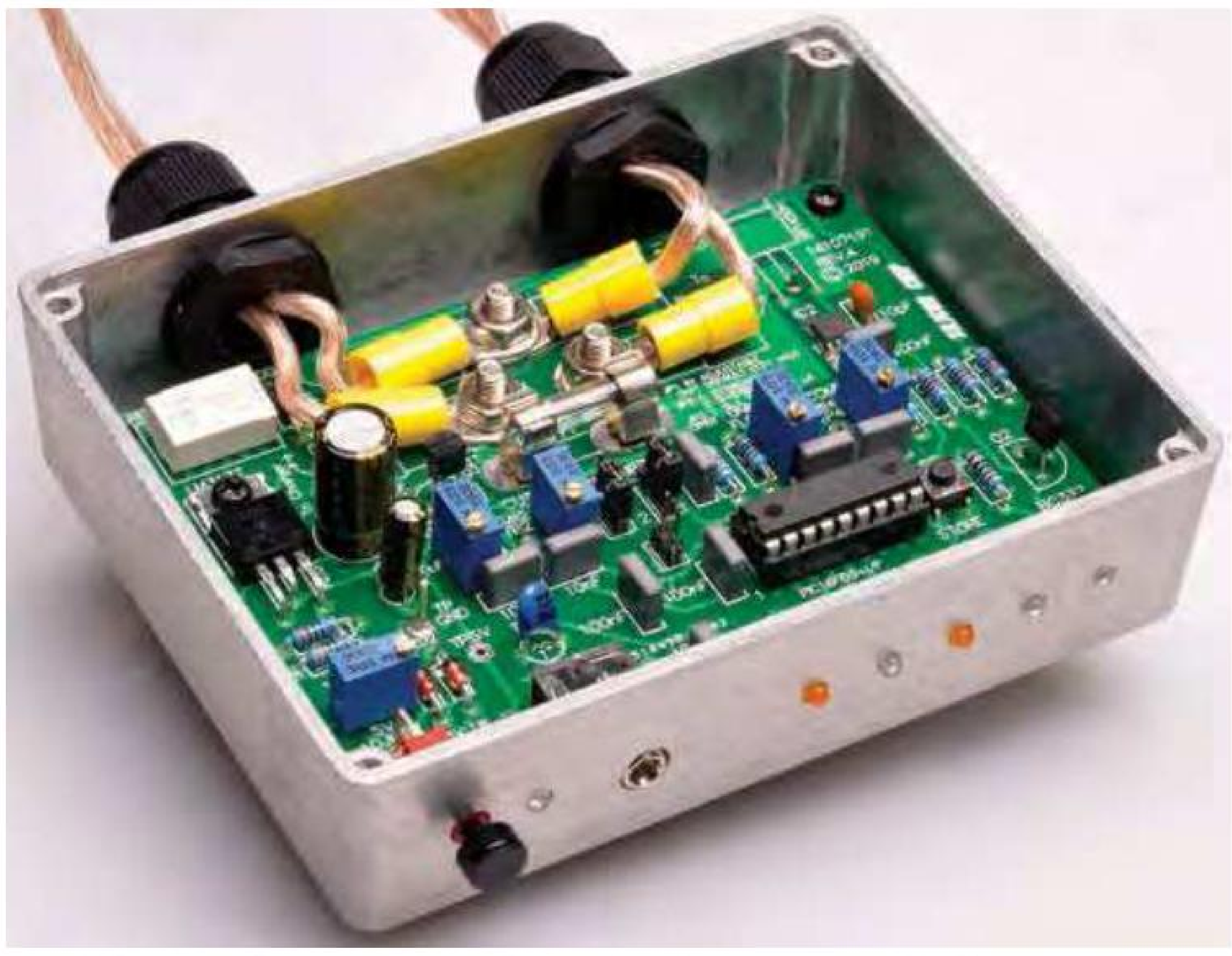
Construction can now continue by installing the fixed resistors. Take care to place each resistor in its correct position. It's best to use a multimeter to check each set of resistors before fitting them because the colour bands can be hard to read.

Next, fit the optional PC stakes for the test points labelled TP GND, TP5V and TP1-TP4. They make it easier to attach clip leads during set-up. Then mount the 2-way header for JP1 and the 3-way headers for JP2 and JP3. Now install the diodes and zener diodes, with the orientations and positions shown in Fig.8.

IC1's socket can then be installed, and this must also be oriented correctly. Follow with tactile pushbutton switch



Fifteen holes are required in the diecast box – eight on the front panel (see below), two on the rear panel (for the cable glands) and five in the base. Four of these are for PCB mounting, with the 6.3mm pillars already shown fitted here. The last hole, just visible in the top right corner, is for mounting Q1 on its insulating washer and bush.



And here's the PCB fitted inside the case with the six LEDs just poking through. As yet, we haven't fitted the front panel artwork (Fig.9, below). And the wiring we used here was just for testing – polarised 15A auto figure-8 should be used.

S2, then jack socket CON1. Push both all the way down onto the PCB before soldering their pins.

Fit the on-board NTC thermistor and capacitors next. Note that the electrolytic capacitors must be oriented with the polarity shown.

In each case, the longer lead is positive, and the stripe on the can indicates the negative lead. Install transistors Q2 and Q3, then trimpots VR1-VR5, taking care to fit the 100Ω trimpot for VR5.

Mount REG1 on the top side of the PCB, with its leads bent down to insert into its pads. Secure the regulator tab to the PCB with a 10mm M3 screw and nut before soldering and trimming the leads.

Follow by fitting RLY1, ensuring that its striped (pin 1) end faces to the right as shown.

Fuse F1 comprises the two fuse clips and the fuse. The fuse clips must be oriented with the end stops facing outwards so that the fuse can be clipped into place. Make sure they're sitting flat on the PCB and then attach them using a hot iron and plenty of solder.

The LEDs are mounted at right angles to the PCB. Bend the leads 11mm back from the front lens of each, taking care to have the anode (longer lead) to the right and then bend the leads downward. Insert into the PCB and solder them so that the bottom of the lenses are 6mm above the top surface of the board.

Now mount pushbutton S1, ensuring it is pressed down firmly onto the board before soldering its pins.

Secure the tapped spacers to each corner of the PCB using 5mm M3 screws, then mount Q1. It's fitted to the underside of the PCB and bolted to the case for heatsinking.

Bend Q1's leads up at right angles, as in Fig.10. It is placed so that the metal face will sit at the base of the enclosure.

Note that the tab of Q1 must be at least 1mm away from the back edge of the case, to prevent the tab shorting to it. Test that it is in the right position by temporarily mounting the PCB in position and mark out the mounting hole for Q1. Also mark out the two holes for the cable glands.

Then remove the board, drill the MOSFET mounting hole to 3mm and deburr. Also drill the cable gland holes and check that they fit securely.

The MOSFET is secured with a 10mm M3 machine screw and nut. If you find it awkward to secure it, the screw can be fed in from the top instead.

Q1's tab must be isolated from the case by an insulating washer and mounting bush. For details, see Fig.10. Now check that the tab of Q1 is insulated from the metal box by measuring the resistance between the two with a multimeter. The reading should be high, above 1MΩ.

The box is isolated from the electrical connections so that accidental contact of the box to a battery terminal will not cause a short circuit. The PCB can now be mounted inside the box using the remaining M3 screws in from the base of the enclosure into the spacers.

Fit the two cable glands and feed the figure-8 cable through them, ready to attach the crimp eyelets. We used the striped side of the wire as the negative and the plain wire as the positive, but some people prefer the opposite. Just make sure you're consistent.

Attach the crimp eyelets to the wire using a suitable crimping tool and secure them to the PCB using the M4 nuts and star washers. Make sure the eyelets are not shorting to adjacent parts, especially the fuse holder.

Attach the large insulated clips to the end of the battery leads; red for positive and black for negative. The *Charge Controller* leads can be terminated in bare copper, for clamping in your charger clips, or they can be permanently wired to the charger. Finally, push the button cap onto S1 and fit the four stick-on rubber feet to the underside of the box.

Preparing the external thermistor

The NTC thermistor on the PCB gives acceptable results with the *Charge Controller* close to the battery, as the metal box will not usually heat up too much above ambient

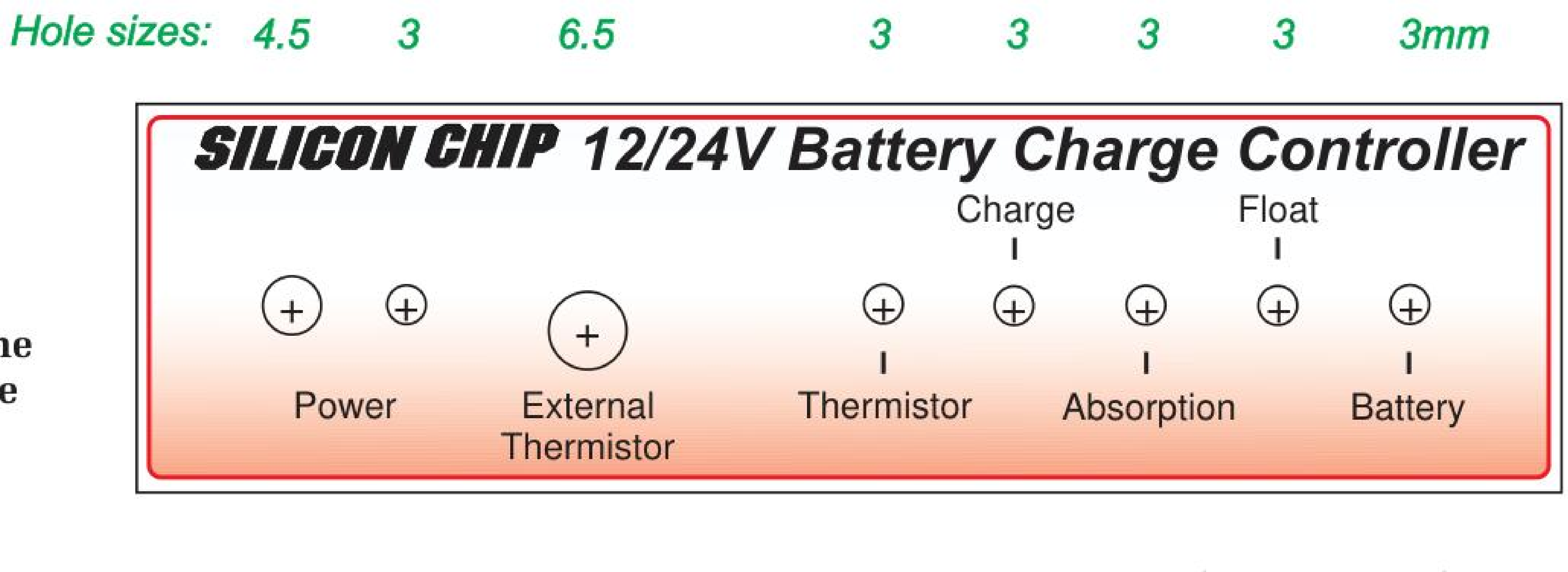

Hole sizes: 4.5 3 6.5 3 3 3 3 3mm
SILICON CHIP 12/24V Battery Charge Controller
Charge
Float
Power
External Thermistor
Thermistor
Absorption
Battery

Fig.9: this front panel artwork can be copied, laminated and glued to the front panel. It could also be photocopied and used as a template for drilling the front panel holes, once you have established the PCB position. You can also download the panel artwork from the December 2020 page of the *PE* website.

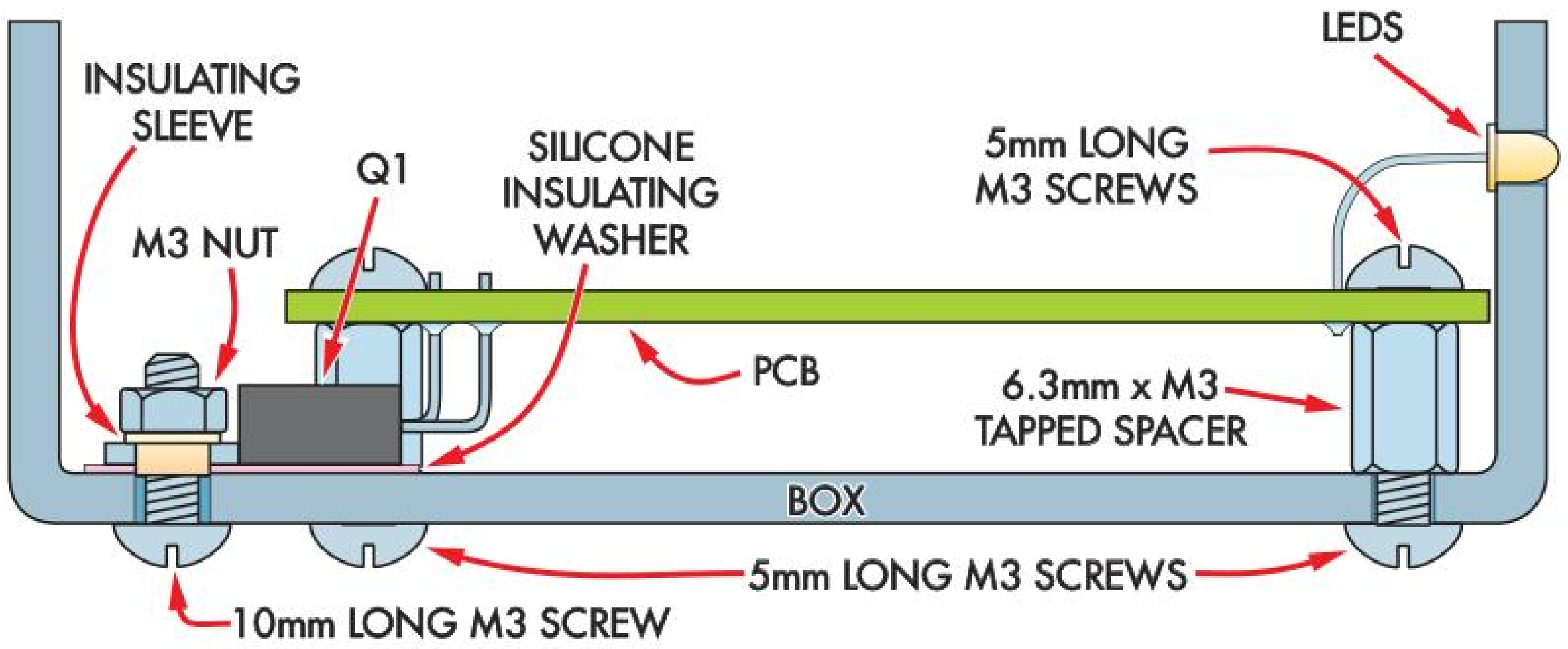


Fig.10: this diagram clarifies how Q1, the LEDs and the PCB itself are mounted in the case. Note the insulating washer and bush (sleeve) under the M3 nut securing Q1, which are critical, as Q1's tab must be electrically isolated from the case.

temperature. As a consequence, its temperature should be similar to the battery temperature. But a thermistor on the battery is going to give more accurate results and therefore a safer and more complete charge.

To make this external thermistor, a stereo 3.5mm jack plug is soldered to one end of the twin-core cable, with the thermistor soldered across the wires at the other end. For the jack plug, connect the internal wires to the tip and ring terminals, and the wire sheath to the jack plug sleeve.

The thermistor can be covered in heatshrink tubing and attached to the side of the battery using adhesive-backed hook-and-loop tape (eg, Velcro) or good quality double-sided tape for a more permanent installation.

Testing

Before applying power, it is vital to adjust VR5 to its lowest resistance by turning the adjusting screw 20 full turns anti-clockwise. You can check that this has been done correctly by measuring the resistance between TP GND and the 330Ω resistor at the end near the cathode of ZD1. The resistance should be near to 0Ω. This prevents REG1 from producing more than 5V when power is first applied.

Now connect a multimeter set to read DC voltage between TP GND and TP5V. Connect a power supply to the charger input (eg, a 12V DC plugpack or bench supply), press and hold S1 and adjust VR5 for a 5.0V reading on the multimeter.

Check that the voltage between the pin 5 and pin 14 pin on IC1's socket is also 5V. If so, switch off power and insert IC1, taking care to orient it correctly and make sure all its pins go into the socket and don't fold up under the IC body. Plug jumpers into JP1, JP2 and JP3 as required for your battery.

Determine the maximum safe charging current

Most lead-acid batteries can accept up to 30% of the quoted Ah capacity as charge current. For example, a 30Ah battery can be charged at 9A. In this case, as long as your charger is rated at no more than 9A, the 100% setting can be used.

If your battery is rated in RC (reserve capacity), you will need to convert to Ah to calculate its maximum charge current. Reserve capacity indicates how many minutes a fully-charged battery can deliver 25A before the voltage drops significantly. A battery with an RC of 90 will supply 25A for 90 minutes.

The amp-hour specification (Ah) refers to the total current that can be supplied over a long period, usually 20 hours. So a 100Ah battery can supply 5A for 20 hours. To convert from RC to Ah, multiply the RC value by 0.42, which is the same as multiplying by 25A to get the capacity in amp-minutes, then dividing by 60 to convert from minutes to hours.

In practice, because the RC capacity specification uses 25A, the conversion from RC to Ah often gives a lower Ah value than the battery's actual capacity. This is because the

Parts list – Clever Charger

1 double-sided PCB, code 14107191, 111 × 81mm
1 diecast aluminium box, 119 × 94 × 34mm [eg, Jaycar HB5067]
1 2A DPDT 5V coil telecom relay (RLY1) [eg, Altronics S4128B]
1 PCB-mount SPDT momentary pubutton switch (S1) [Jaycar SP0380, Altronics S1498]
1 pushbutton switch cap for S1 [Altronics S1482, Jaycar SP0596]
1 SPST micro tactile switch with 0.7mm actuator (S2) [Jaycar SP0600, Altronics S1122]
1 PCB-mount 3.5mm stereo switched socket (CON1) [Altronics P0092, Jaycar PS0133]
2 PCB-mount M205 fuse clips (F1)
1 10A M205 fuse (F1)
2 NTC thermistors (10kΩ at 25°C) (TH1 and external thermistor)
1 2-way header with 2.54mm spacing (JP1)
2 3-way headers with 2.54mm spacing (JP2,JP3)
3 jumper plugs/shorting blocks (JP1-JP3)
1 18-pin DIL IC socket (for IC1)
1 3.5mm stereo jack plug
1 TO-220 silicone insulating washer and mounting bush (for Q1)
4 6.3mm-long M3 tapped spacers
3 M4 × 10mm machine screws
3 M4 star washers
3 M4 hex nuts
2 M3 × 10mm machine screws
8 M3 × 5mm machine screws
2 M3 hex nuts
4 insulated crimp eyelets (wire size 4mm, eyelet for M4 screw)
2 cable glands for 4-8mm diameter cable
1 2m length of 15A figure-8 automotive cable
1 1m length of twin-core shielded cable (for thermistor)
1 20mm length of 6mm diameter heatshrink tubing
2 large insulated battery terminal alligator clips (red and black)
6 PC stakes (optional)
4 small adhesive rubber feet

Semiconductors
1 PIC16F88-I/P micro programmed with 1410719A.HEX (IC1)
1 Si8751AB-IS isolated FET driver (IC2) (mouser.co.uk)
1 LM317T 1.5A adjustable positive regulator (REG1)
1 IRF1405N N-channel MOSFET (Q1)
2 BC337 NPN transistors (Q2,Q3)
3 green 3mm LEDs (LED1,LED5,LED6)
2 orange 3mm LEDs (LED2,LED4)
1 red 3mm LED (LED3)
2 18V 1W zener diodes (ZD1,ZD2)
3 1N4004 1A diodes (D1-D3)

Capacitors
1 220µF 50V PC electrolytic
1 100µF 16V PC electrolytic
5 100nF MKT polyester
5 10nF MKT polyester
1 10pF ceramic

Resistors (all 0.25W, 1% metal film unless otherwise stated)
1 100kΩ 1 51kΩ 3 10kΩ 1 3.3kΩ 1 2kΩ
7 1kΩ 1 330Ω 1 120Ω 1 100Ω 1W, 5% 1 56Ω
4 10kΩ multi-turn top adjust trimpots, 3296W style (VR1-VR4) (code 103)
1 100Ω multi-turn top adjust trimpot, 3296W style (VR5) (code 101)

Small Capacitor Codes

Qty.	Value	µF value	IEC code	EIA code
☐ 5	100nF	0.1µF	100n	104
☐ 5	10nF	0.01µF	10n	103
☐ 1	10pF	n/a	10p	10

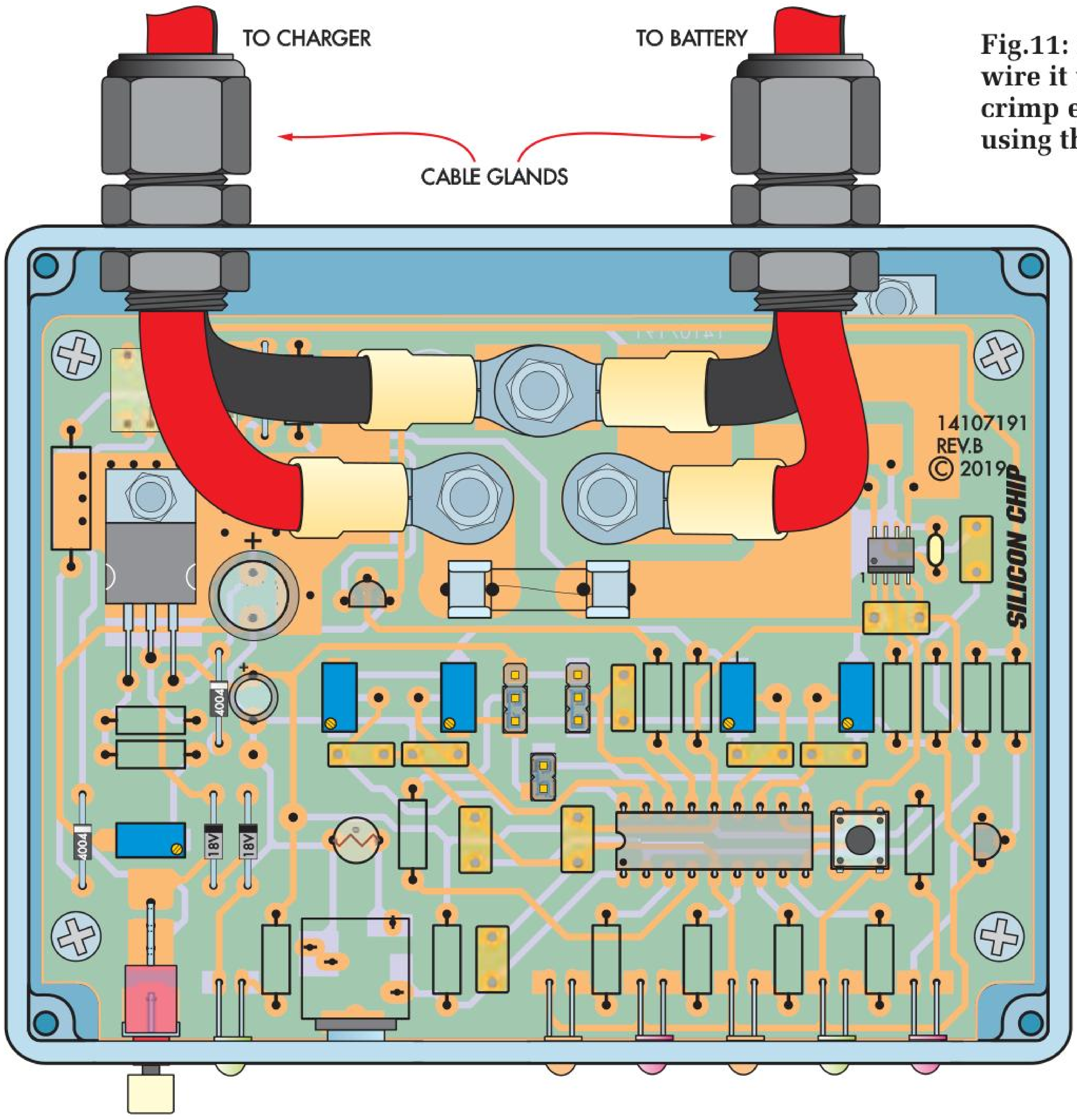


Fig.11: once the PCB is mounted in the case, wire it up as shown here. Make sure that the crimp eyelets are firmly secured to the board using the specified washers and nuts.

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Ah capacity usually requires much less current from the battery, over a longer period.

Setting the charge current

For most large batteries, you would set the charge rate to 100%. To do this, adjust VR1 to get a reading of at least 1V at TP1 relative to TP GND. You can use the 100% setting for all batteries that can accept the full charge rate from your charger.

If you need a lower current than your charger would normally supply, as explained above, adjust VR1 to reduce the maximum charge rate.

This still applies the full current from the charger to the battery but in bursts. For example, when the charge percentage is set at 50%, the charge will be bursts of full current for 50% of the time.

This would be suitable, for example, with a charger that is rated at 4A and a battery that can only accept a 2A charge current.

Divide the desired charge rate percentage by 100 and adjust VR1 to get this voltage at TP1. So for our 50% example, you would adjust for 0.5V at TP1.

Note that when charging a 12V battery that initially has less than 10.5V across its terminals, or a 24V battery with less than 21V, the actual charge rate will be 1/10th of that set. So for example, if you have set the charge rate to 100%, it will be charged with a burst for 200ms every two seconds. During this process, the Charge, Absorption and Float LEDs flash.

Once the voltage comes back up into the normal range, full-rate charging will start.

Current limiting

Very small batteries may not tolerate these high-current bursts, even if they are limited in time. In this case, you could add a series power resistor between the *Charge Controller* and your battery.

For example, when using a 12V battery and with a charger that typically provides up to 17V peak, there will be 5V peak across the resistor. So the resistor value required is 5V divided by the peak current that the battery can tolerate. If the peak current is 1A, then the resistance can be 5Ω (eg, one 4.7Ω resistor or two 10Ω resistors in parallel).

Its wattage rating will need to be 5V squared (25) divided by 5Ω. That gives us a 5W dissipation, so to be safe, you would use a 4.7Ω 10W resistor, or two 10Ω 5W resistors in parallel.

This is a conservative figure since 5W is the peak power, not necessarily the average power. The actual RMS voltage across the resistance will be around 30% lower than this, so the dissipation will be around 50% lower. Therefore, you could probably get away with a 5W resistor.

As mentioned, the charge LED can be set to flash when current is applied during the absorption and float phases. This indicates the duty cycle used to charge the battery.

If the LED is off, then the battery is over the required voltage for absorption or float. If the LED is not lit very often, then the battery is at the required voltage. If the LED is lit continuously, then the battery voltage is still being brought up.

LED option setting

The flashing LED option is on initially. If you do not require the charge LED to show during these phases, you can disable this. Switching off power and holding S2 while the power is re-applied using S1 will disable this feature.

The change is acknowledged by a minimum of two fast (two per second) flashes of the Charge LED. The acknowledgement flashing continues until S2 is released. You can re-enable the feature by holding S2 again at power up.

Setting the parameters

Most battery manufacturers will specify the required cut-off voltage (also called the cyclic voltage) for a given battery. For lead-acid types, the manufacturer will typically also specify the float voltage (also called the trickle voltage) and the temperature compensation coefficient. Note that the cut-off and float voltages must be the values specified at 20°C.

The temperature compensation required by manufacturers is usually shown as a graph of voltage versus temperature.

You can convert this to mV/°C by taking the difference between the voltages at two different temperatures and divide by the temperature difference.

For example, a battery graph may show the cut-off or cyclic voltage at 0°C to be 14.9V. At 40°C, it may be 14.2V. So $(14.2\text{V} - 14.9\text{V}) \div 40°\text{C} = -700\text{mV} \div 40°\text{C} = -17.5\text{mV}/°\text{C}$. Where the float temperature compensation is different from the cyclic temperature compensation, a compromise between the two values will have to be made.

Note that you can do this calculation over a smaller temperature range if that is consistent with the temperatures under which you expect to be charging the battery, eg, 10-35°C if you live in coastal Sydney, but different in the UK!

To set the adjustable parameters, apply power to the *Charge Controller* via a battery or charger and select the battery type with JP3.

Then connect a multimeter between TP2 and TP GND and adjust for one-tenth of the required cut-off voltage using VR2. So 1V at TP2 represents a 10V cut-off, 1.44V sets it to 14.4V, and so on.

Now monitor the voltage at TP3 and adjust VR3 for the required float voltage with the same 10:1 ratio.

For the temperature compensation, monitor TP4 and adjust VR4 for the required compensation, with 1V representing –10mV/°C. So 5V represents –50mV/°C and 2V represents –20mV/°C, and so on.

Once you've adjusted all these, make sure JP1 is inserted and then press S2 to store the values.

The Thermistor, Charge and Float LEDs will all flash twice to acknowledge that these values have been stored successfully for lead-acid batteries. If adjusting the thresholds for $LiFePO_4$ batteries, just the charge LED and absorption LED will flash.

You can store the parameters for each battery type by changing the settings for JP3 and readjusting the trimpots, then store the values again using switch S2. Adjusting the trimpots without pressing S2 has no effect.

The adjustment of VR1, for the charge rate, is different. This has an immediate effect. You will have to re-adjust it each time you switch to charging a different battery that needs a different charge rate than the last one.

Charge Controller limitations

To round out our description of this project, we should also mention its possible shortcomings. These do not matter in most cases, but may be significant in specific charging applications.

(1) Pulsed operation

The pulsed charging current can cause extra heating within the battery as losses are proportional to the square of the current. For example, when charging at an average of 1A from a 4A charger, a 25% duty cycle is used. This averages to 1A, however, the losses are equivalent to charging at $4A^2 \times 25\% = 4$ times that of charging at 1A continuously.

(2) Absorption and float charge

We pulse the charge current, therefore the battery voltage fluctuates during charging. We measure the battery voltage just after the charge pulse finishes. Compared to a charger that has continuous charging at a lower current, the battery voltage may be maintained at a different value.

(3) Charge indication

As the battery supplies the circuit power via Q1's body diode, it can appear that charging is taking place even when the charger is not connected or powered. It is important to check that the charger is connected and is switched on when you start charging.

(4) Battery discharge

If the 'dumb' charger is switched off with the battery connected, the battery will eventually discharge due to the 50mA load of the Charge Controller. This is prevented using a relay to switch off the power to the charge controller if the battery voltage drops too low, but if this happens, you will have to recharge the battery.

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This series of articles provides a broad-based introduction to choosing and using a wide range of test gear, how to get the best out of each item and the pitfalls to avoid. It provides hints and tips on using, and – just as importantly – interpreting the results that you get. The series deals with familiar test gear as well as equipment designed for more specialised applications.

The articles have been designed to have the broadest possible appeal and are applicable to all branches of electronics. The series crosses the boundaries of analogue and digital electronics with applications that span the full range of electronics – from a single-stage transistor amplifier to the most sophisticated microcontroller system. There really is something for everyone!

Each part includes a simple but useful practical test gear project that will build into a handy gadget that will either extend the features, ranges and usability of an existing item of test equipment or that will serve as a stand-alone instrument. We've kept the cost of these projects as low as possible, and most of them can be built for less than £10 (including components, enclosure and circuit board).

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LFSR Random Number Generator Using Logic ICs

By combining just a few logic ICs, it is possible to digitally generate a pseudo-random number sequence. There are two reasons why you might want to build this circuit: one, it's interesting and will help you learn how logic ICs work. And two, it can do something useful: it can generate LED patterns to display on our very popular *Stackable LED Christmas Tree* that we published in last month's issue.

by Tim Blythman

The LED Christmas Tree is electrically quite simple: it takes a DC power source and a serial data stream, and switches the dozens or even hundreds of LEDs on and off to create the pattern that's described by that serial data.

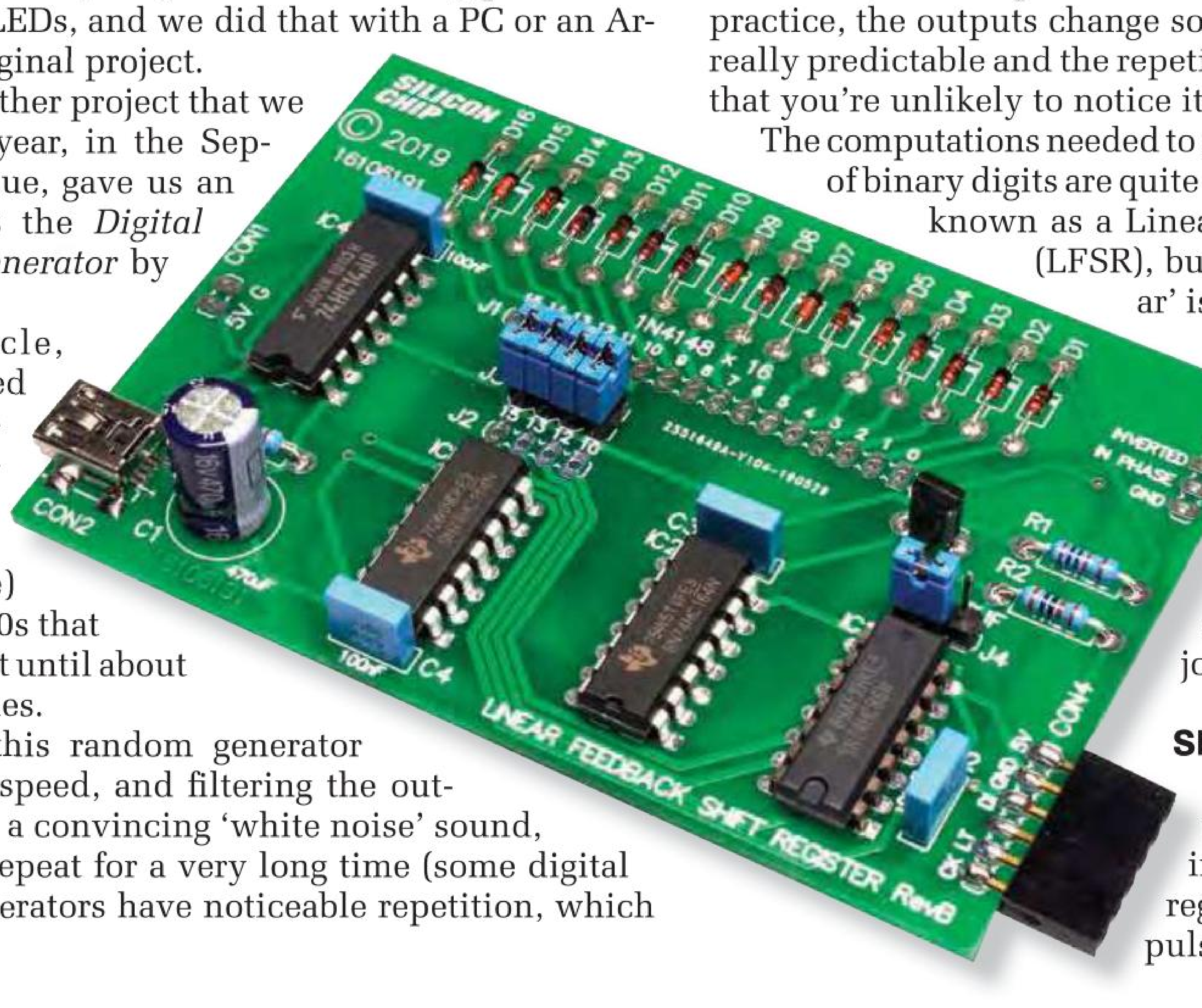
This simplicity is its strength; its low per-board cost and expandability mean that you can build an impressive *LED Christmas Tree* display without spending much money.For more information on that *LED Christmas Tree* project, see the November 2020 issue.

You do need a way to generate interesting patterns to show on those LEDs, and we did that with a PC or an Arduino in the original project.

However, another project that we published last year, in the September 2019 issue, gave us an idea. That was the *Digital White Noise Generator* by John Clarke.

In that article, John programmed a small microcontroller to produce a seemingly random (but not quite) series of 1s and 0s that would not repeat until about four billion cycles.

By running this random generator at quite a high speed, and filtering the output, it produces a convincing 'white noise' sound, which doesn't repeat for a very long time (some digital white noise generators have noticeable repetition, which is annoying!).



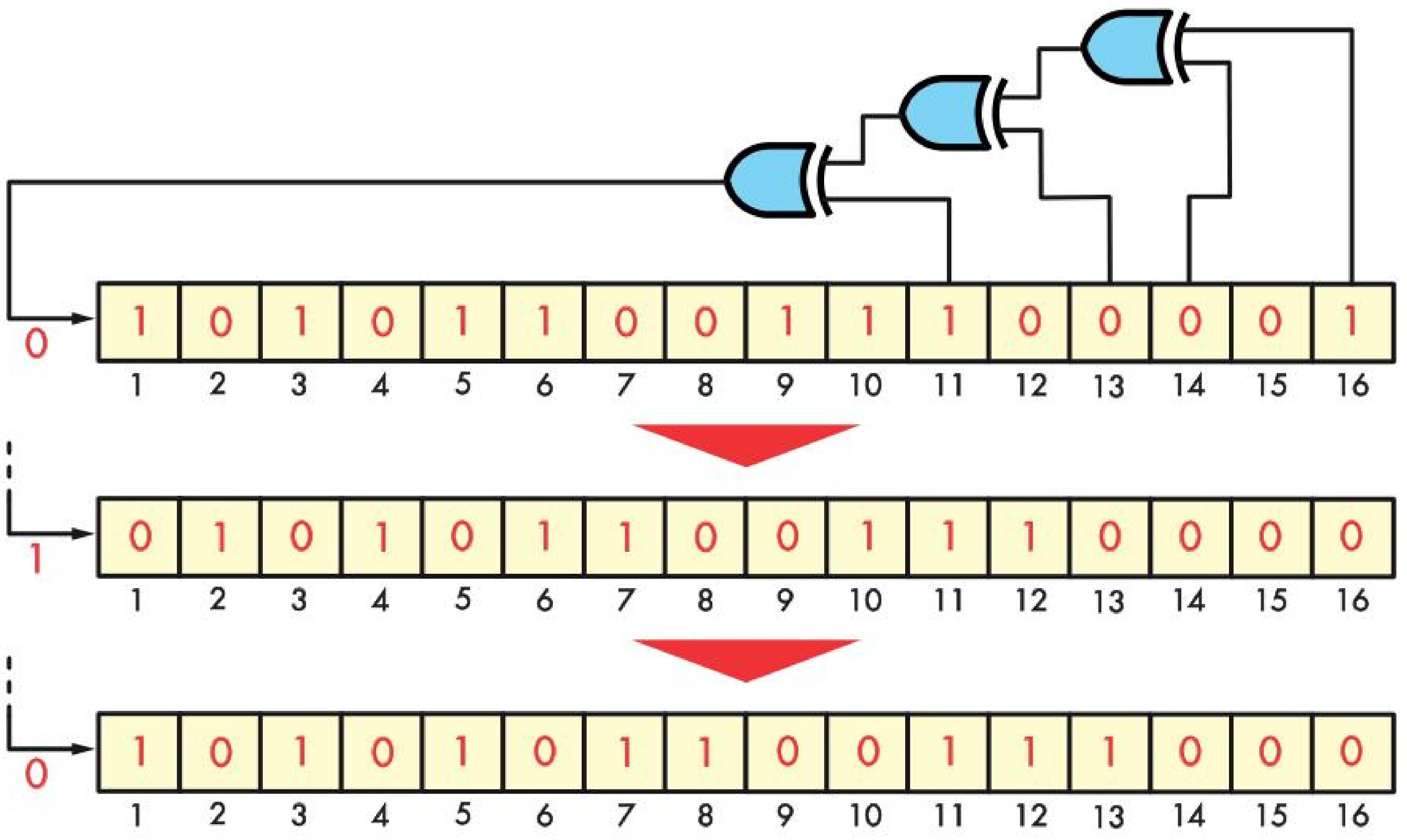
So we've combined a couple of shift register chips with a few other bits and pieces to make a similar random number generator without using a microcontroller. And we've made it so that you can use it to drive the *LED Christmas Tree*, or just as a way to investigate and understand its principle of operation. It's nice and simple, so it's easy to build and straightforward to understand.

We describe it as 'pseudo-random' and not truly random because if you know the current state, you can predict the next state, and the pattern does eventually repeat. But in practice, the outputs change so fast that the output is not really predictable and the repetition period is long enough that you're unlikely to notice it.

The computations needed to generate this random string of binary digits are quite simple. This is a technique known as a Linear Feedback Shift Register (LFSR), but note that the word 'linear' is not used here in the electronic sense – we'll have more on that shortly. That means that you don't necessarily need a microcontroller to use this technique. Old-fashioned discrete shift registers can do the job, too.

Shift register basics

Fig.1 shows how a shift register works. Data is fed into one end of the shift register, and on each clock pulse, that value (zero or one)

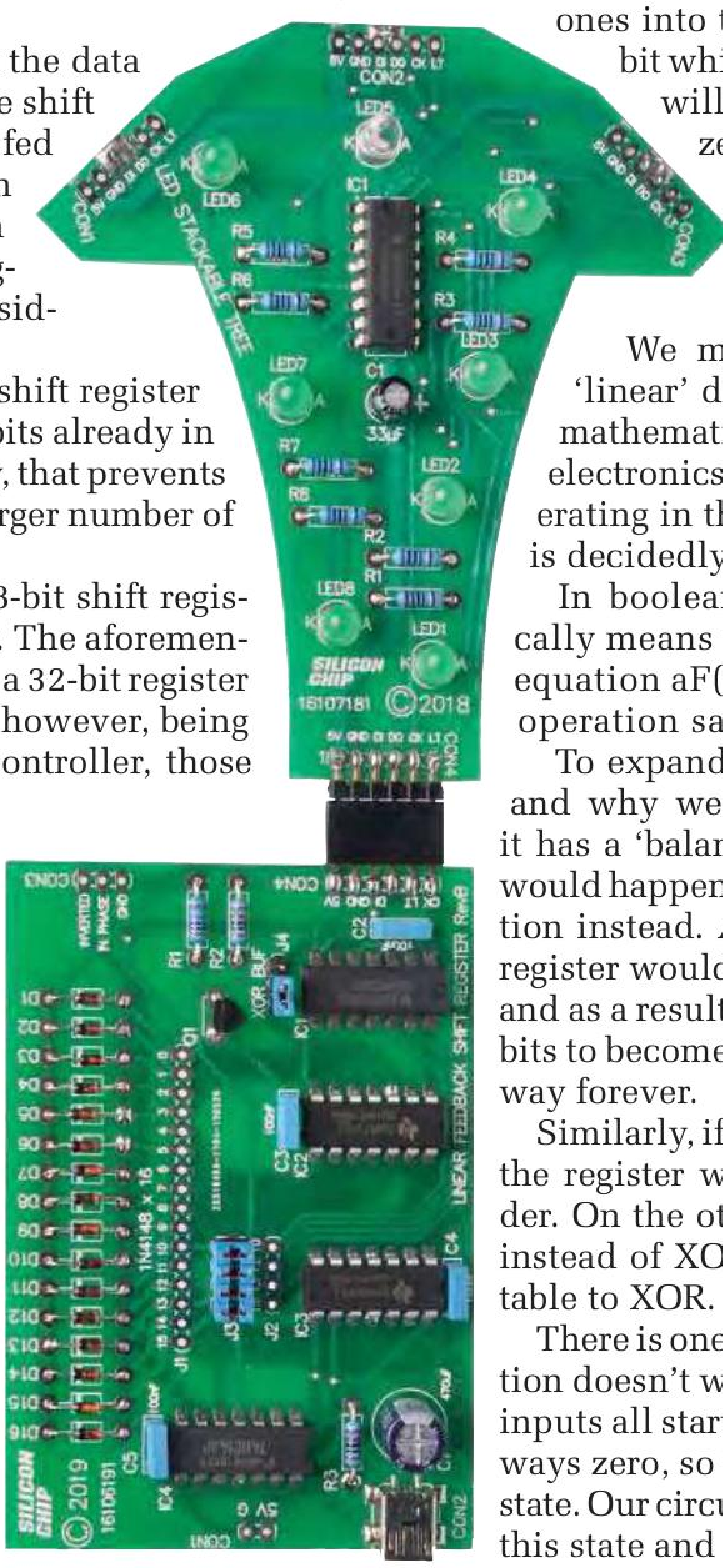


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	1	0	1	0	1	1	0	0	1	1	1	0	0	0	0	1
1	0	1	0	1	0	1	1	0	0	1	1	1	0	0	0	0
0	1	0	1	0	1	0	1	1	0	0	1	1	1	0	0	0

Fig.1: this shows one way of building a 16-bit LFSR with a maximum non-repeat interval of 65,535 clocks. It's a relatively simple method, so it's the one we've chosen to use in this project. The binary values in each cell move one step to the right in time with the clock signal. The XOR gates calculate a new bit value which is fed in as the first bit of the sequence. Three iterations of the pattern are shown.

is loaded into the first position in the shift register. The data which was previously in the first position then moves into the second position, and so on until the last value which used to be in the last position 'falls out' and may go on to be used elsewhere, or is simply discarded.

Some shift registers also include an output latch, so that you can shift all new data into the register without the output states changing, and the new data is then fed through to the output latches when a separate clock pin is pulsed. We don't need that sort of function in this project: the shift register ICs we're using update their output states the instant that they receive a clock pulse.



Generating random numbers

The idea behind the LSFR is to feed back the data which is about to 'fall out' of the end of the shift register back to the input side. But it isn't fed back as-is, because if it were, the pattern would repeat every eight cycles for an 8-bit register, or 16 cycles for a 16-bit register. That's far too predictable to be considered random.

However, if the data coming out of the shift register is combined with the state of some of the bits already in the shift register, even in a very simple way, that prevents the pattern from repeating until a much larger number of steps have occurred.

In our circuit, we have combined two 8-bit shift register ICs to form a single 16-bit shift register. The aforementioned *Digital White Noise Generator* used a 32-bit register which gave a much longer repeat period; however, being implemented in software using a microcontroller, those extra bits didn't take up physical space.

We decided that having four shift register ICs, plus the supporting componentry, would be too large; after all, we want to keep this device simple, so you can easily see how it works. And anyway, the *Digital White Noise Generator* had a high clock rate of around 154kHz, which was necessary to produce pleasant-sounding noise over the audio bandwidth of 20Hz-20kHz.

In this example, we want to be able to see the patterns generated, so even if you are updating a large set of LEDs quite rapidly, you don't need a clock rate of more than a couple of kilohertz. So despite the much smaller register size, the repetition period is still quite long.

The way that we are combining the output of the shift register with some of its contents is a basic boolean logic operation called 'exclusive or', abbreviated to 'XOR'. A two-input XOR has a balanced truth table, with four possible input combinations (00, 01, 10, 11) and the result is equally likely to be a zero or a one (00 => 0, 01 => 1, 10 => 1, 11 => 0).

This is important, because operations which do not produce an equal number of zero or one outcomes for a random distribution of input values will rapidly cause the bits in the register to become all zero or all one; *not* what we want when we are trying to generate a random-looking pattern!

By the way, we haven't explained how the random values translate into light patterns, but hopefully you have figured it out: we can feed the 'random' series of zeros and ones into the *Christmas Tree* and for each bit which is one, the corresponding LED will be on, and for each bit which is zero, it will be off. If we shift these values in rapidly, the LEDs will appear to twinkle, like stars.

Linear operations in logic

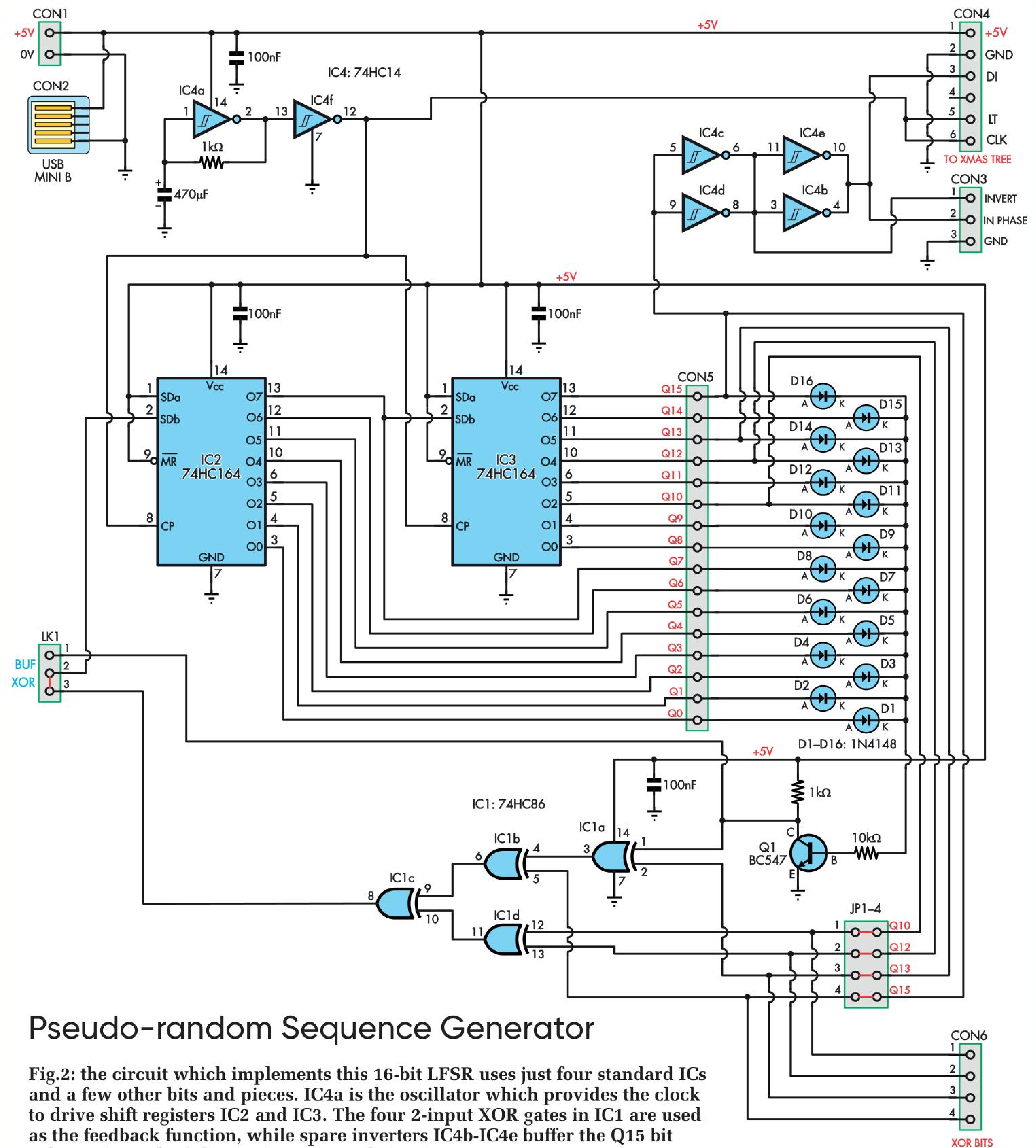
We mentioned earlier that the term 'linear' does not mean the same thing in mathematics as it does in electronics. In electronics, it suggests that the circuit is operating in the analogue domain; this circuit is decidedly digital.

In boolean logic, the term 'linear' basically means that the function F satisfies the equation $aF(x + y) = aF(x) + aF(y)$. Our XOR operation satisfies that condition.

To expand on why XOR is a good choice, and why we said earlier that it's good that it has a 'balanced' truth table, consider what would happen if we used the similar AND function instead. A zero at the output of the shift register would always give a zero at the input, and as a result, it wouldn't take long for all the bits to become zero. They would then stay that way forever.

Similarly, if we used an OR function instead, the register would fill with ones in short order. On the other hand, XNOR could be used instead of XOR, as it has a very similar truth table to XOR.

There is one scenario in which the XOR function doesn't work well, and that's when all the inputs all start as zero, as then the output is always zero, so the register will get stuck in this state. Our circuit has extra components to detect this state and override the output in that case.


CON1
+5V
0V
CON2
USB MINI B
100nF
IC4: 74HC14
IC4a
IC4f
1kΩ
470µF
+5V
CON4
+5V
GND
DI
LT
CLK
TO XMAS TREE
IC4c
IC4e
IC4d
IC4b
CON3
INVERT
IN PHASE
GND
+5V
100nF
100nF
SDa
SDb
MR
IC2
74HC164
CP
Vcc
GND
O7
O6
O5
O4
O3
O2
O1
O0
IC3
74HC164
CON5
Q15
Q14
Q13
Q12
Q11
Q10
Q9
Q8
Q7
Q6
Q5
Q4
Q3
Q2
Q1
Q0
D16
D15
D14
D13
D12
D11
D10
D9
D8
D7
D6
D5
D4
D3
D2
D1
A
K
D1–D16: 1N4148
LK1
BUF
XOR
+5V
100nF
1kΩ
IC1: 74HC86
IC1a
IC1b
IC1c
IC1d
Q1
BC547
C
B
E
10kΩ
JP1–4
Q10
Q12
Q13
Q15
CON6
XOR BITS

Pseudo-random Sequence Generator

Fig.2: the circuit which implements this 16-bit LFSR uses just four standard ICs and a few other bits and pieces. IC4a is the oscillator which provides the clock to drive shift registers IC2 and IC3. The four 2-input XOR gates in IC1 are used as the feedback function, while spare inverters IC4b-IC4e buffer the Q15 bit value so it can be fed to various external circuits.

We have also carefully chosen which bits are XORed together to ensure our sequence does not repeat prematurely.

With a 16-bit linear feedback shift register and well-chosen 'taps', we can cycle through 65535 ($2^{16} - 1$) states before the sequence repeats.

With a 2Hz update rate, that means the sequence will take over nine hours to repeat. The taps we're using are shown in Fig.1. These guarantee the maximum repetition period, as stated above. (See the September 2019 *Digital White Noise Generator* article for more background on how a pseudo-random number generator works.)

Circuit description

The *Pseudo-random Sequence Generator* circuit is shown in Fig.2. We've kept it as simple as possible, so it's based on just four logic ICs, one transistor, sixteen diodes and a handful of resistors and capacitors.

IC2 and IC3 are the two eight-bit shift registers, and they are cascaded to form a single 16-bit shift register. This is done by holding the O7 output of IC2 to the SDb input (pin 2) of IC3, tying the clock input pins (pin 8 of each IC) together and holding the SDa and $\overline{\text{MR}}$ pins high. This means that the SDb input determines the input state of the shift register, and the chips are always active.

As a result, the value of a bit fed into pin 2 of IC2 (zero or one) will appear 16 clock pulses later at pin 13 of IC3. Pins 3-7 and 10-13 of both ICs are outputs carrying the values of the individual bits from each shift register.

The common clock pins are driven from pin 12 of IC4f, a Schmitt trigger inverter, which buffers the output of oscillator IC4a. This is another Schmitt trigger inverter with a resistor and capacitor in the feedback loop, causing it to oscillate at around 2Hz. You can change this frequency by varying either the resistor or capacitor values; increase either to slow it down or decrease either to speed it up.

It's important that a Schmitt trigger inverter is used for this oscillator since the built-in hysteresis (ie, the difference in positive-going and negative going input switching voltage thresholds) ensures that it oscillates and also makes the frequency fairly predictable.

XOR gates

IC1 is a 74HC86 quad XOR gate. The four gates are combined to effectively provide a single five-input XOR gate, with these inputs being at pins 1, 2, 5, 12 and 13 and the result is available at pin 8.

Usually, jumpers JP1-JP4 will be inserted, and LK1 will be in the position shown in Fig.2, so four of these inputs are connected to outputs Q10, Q12, Q13 and Q15 of the shift register. This gives us the configuration shown earlier in Fig.1, with one additional XOR input.

Parts list – Pseudo-Random Sequence Generator

1 double-sided PCB coded 16106191, 91.5mm x 63mm
1 2-pin header (CON1)
1 SMD mini type-B USB socket (CON2; optional)
2 3-pin headers (CON3,LK1)
1 6-way female header (CON4)
1 16-way female header (CON5; optional)
1 4-way female header (CON6; optional)
1 2x4-way pin header (JP1-JP4)
5 jumper shunts (for JP1-JP4 and LK1)
4 14-pin DIL IC sockets (for IC1-IC4; optional)

Semiconductors
1 74HC86 quad XOR gate, DIP-14 (IC1)
2 74HC164 8-bit shift register, DIP-14 (IC2, IC3)
1 74HC14 hex Schmitt trigger inverter, DIP-14 (IC4)
16 1N4148 small-signal diodes (D1-D16)
1 BC547 NPN transistor (Q1)

Capacitors
1 470µF 10V electrolytic
4 100nF ceramic or MKT

Resistors (all 1/4W 5% or 1%)
1 10kΩ
2 1kΩ

This fifth XOR input comes from a 16-input NOR gate, built from diodes D1-D16, NPN transistor Q1 and its two biasing resistors. In practice, what this means is that transistor Q1 is switched on as long as at least one of the Q1-Q16 outputs of the shift register is high (1). In this case, its collector will be low, so the fifth XOR input at pin 1 of IC1a will also be low.

However, if the shift register contains all zeros, none of diodes D1-D16 will be forward biased and so transistor Q1 switches off, allowing the 1kΩ resistor to pull its collector high, to +5V. This then causes the output of our five-way XOR gate to be one, not zero, ensuring that the shift register cannot stay in the all-zeros state for more than one cycle, as a one will be fed into its input in this case.

The output of the XOR gate is normally fed to the shift register input, pin 2 of IC2, via LK1. If LK1 is instead placed in its alternative position, the output of the shift register is merely fed back into the input. Because Q1 prevents it from being all zeros all the time, this has the effect of one output being high, which then moves from one end of the shift register to the other, before repeating.

When this unit is connected to the *LED Christmas Tree*, that causes it to generate a 'chaser' effect as one lit LED moves through the tree every seventeen clock pulses.

Driving external circuitry

The four spare inverters in IC4 (ie, those not used for the oscillator) are paired up to buffer the output of the shift register. The O7 output from pin 13 of IC3 is fed to input pins 5 and 9 of inverters IC4c and IC4d, and their outputs are also paralleled and connected to pin 1 of CON3, to provide a bit more drive current for any external circuitry connected there.

That signal is then similarly re-inverted by IC4b and IC4e, to provide an in-phase buffered output at pin 2 of CON3. This gives us complementary signals at pins 1 and 2 of CON3, which could provide a 10V peak-to-peak signal for driving a piezo (for example).

The in-phase output is also fed to the DI pin of CON4, which has a pinout designed to match the *Stackable LED Christmas Tree*, so it can be used to drive a tree directly. The buffered clock signal is taken to the CLK and LT pins on CON4, so that each bit of pseudo-random data fed to the tree is synchronously shifted all through the tree.

The power supply for this circuit is elementary: a 5V DC externally regulated supply is fed in via either USB socket CON2 or pin header CON1. Bulk bypassing is not required; one 100nF capacitor per IC is sufficient.

Note that the USB socket provides a measure of reverse polarity protection, as the USB plug can only be inserted one way, while there is no protection when using pin header CON1. So be careful when wiring CON1 as you'll fry the board if you reverse it.

Construction

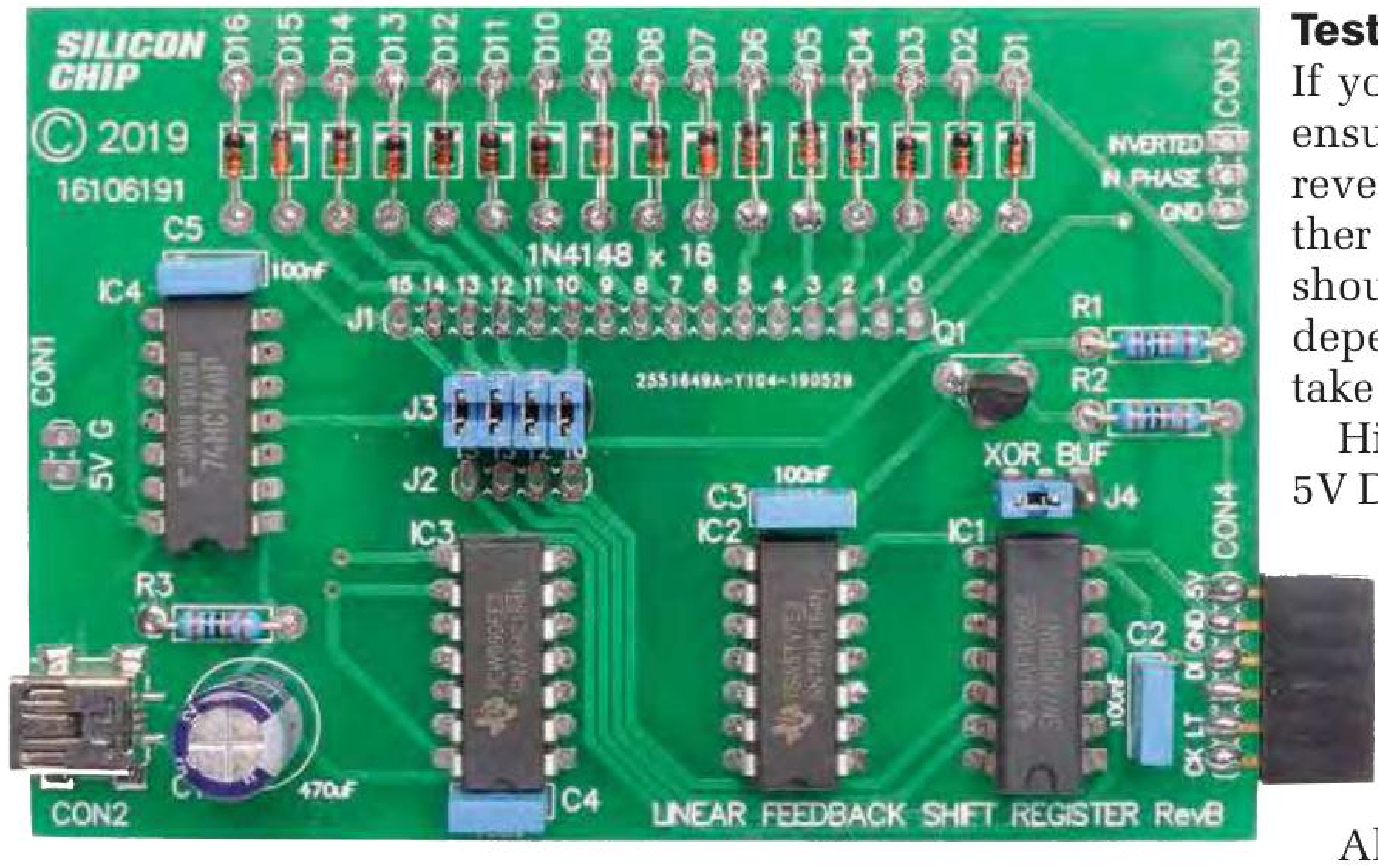
Use the PCB overlay diagram (Fig.3) and the photos as a guide during construction. The *Pseudo-random Number Generator* is built on a PCB coded 16106191, which measures 91.5 x 63mm and is available form the *PE PCB Service*.

If you are fitting CON2, the optional surface-mounted mini-USB socket for power, do this first. Apply some solder flux to the pads on the PCB and locate the socket with its pins into the holes on the PCB. Solder one of the side mechanical tabs in place and ensure that the pins line up with their pads before proceeding.

Load the iron with a small amount of solder and touch the iron to the pads. The solder should flow onto the pad and the pins. Only the two end pins for power are needed. Check that there are no bridges to adjacent pins, and if there are, carefully remove with solder braid or wick. Once you are happy that the power pins are soldered correctly, solder the remaining mechanical pins.

Now move onto the resistors and diodes. Make sure that the diodes are all oriented correctly, ie, with their cathodes stripes towards the top of the board.

Then solder the ICs in place. You can use sockets if you wish. These must also be oriented correctly, with the pin 1 dot/notch in each case towards the bottom of the board. Don't get the chips mixed up since there are three different types, but they all have the same number of pins (14).



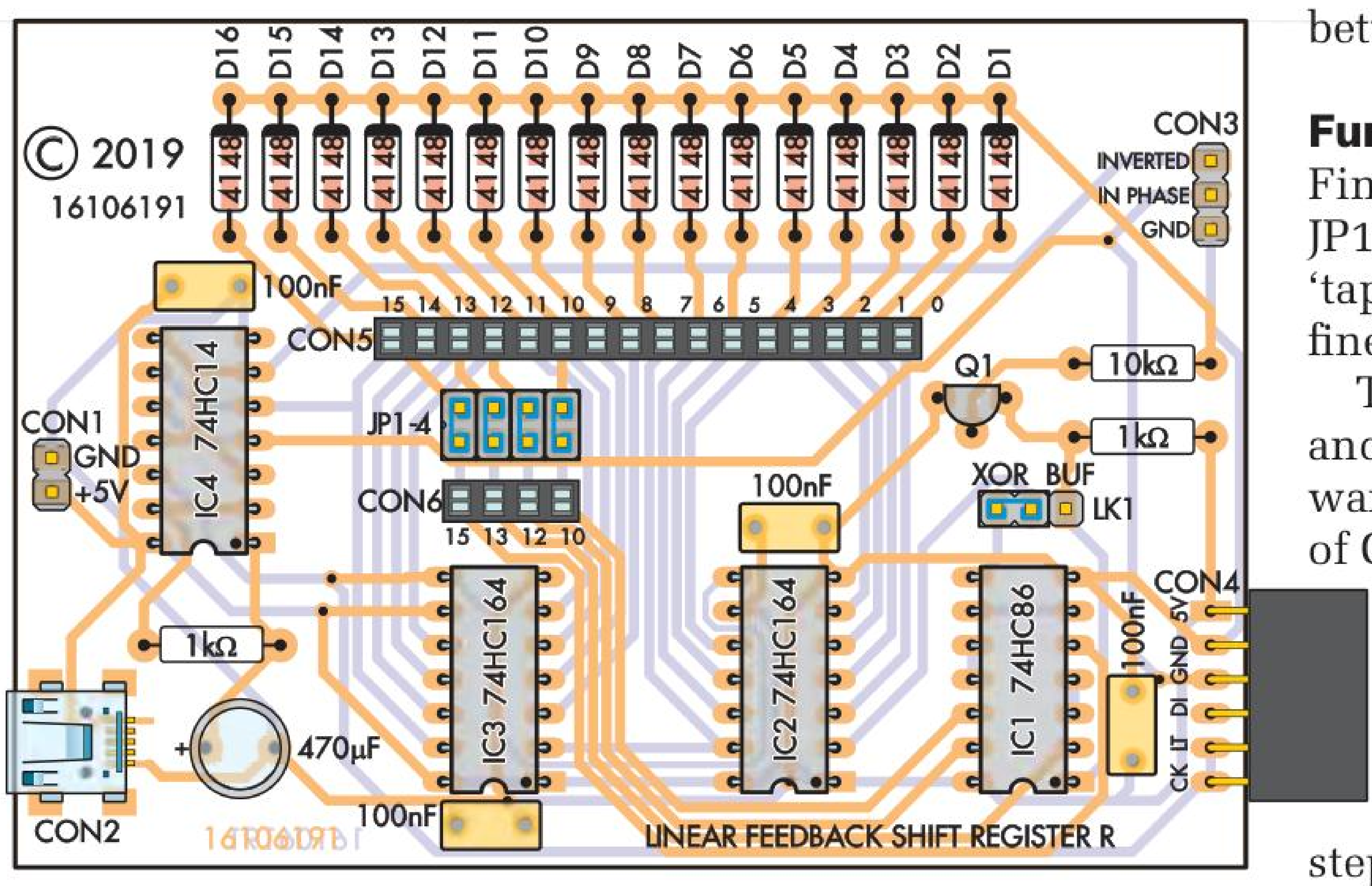


Fig.3: like the circuit, the PCB layout is quite simple. The main thing to watch while building it is the orientations of IC1-IC4 and D1-D16. Various headers and jumpers are provided so you can experiment with and probe the circuit to see what happens if you change it slightly. A header socket is provided to allow the board to directly drive a *Stackable LED Christmas Tree*, with as few as 10 LEDs or as many as several hundred.

You may need to carefully bend the legs on the ICs so that they are straight and vertical before they will fit. Solder two diagonally opposite pins on each IC, then check the orientation and that the IC is flat against the PCB before soldering the remaining pins.

The four small 100nF capacitors are not polarised. Fit them now. Follow with the sole transistor (Q2) with its flat face oriented as shown. You may need to carefully bend its legs to fit the PCB.

Fit the pin headers next, including CON1, CON3, LK1 and JP1-JP4. Follow with header socket CON4, mounted at right-angles, so it can plug into the male header on an *LED Christmas Tree* board. This can be done by surface-mounting it to the pads on top of the PCB rather than soldering it into the through-holes. If you want your tree to project up from this board, CON4 can be fitted vertically instead.

Now fit optional headers CON5 and CON6, if desired. These are provided to allow you to experiment by feeding different combinations of the sixteen shift register outputs into the XOR gate inputs. We've recommended using female headers for these so that so you can make connections using male-male jumper wires, but other combinations are possible. Finally, fit the electrolytic capacitor, ensuring its longer positive lead goes into the hole marked with the '+' sign, then plug jumper shunts into JP1-JP4 and LK1 as shown in Fig.2 and Fig.3.

Testing

If you have a *Christmas Tree* PCB, plug it into CON4, ensuring the pin functions line up correctly (ie, it is not reversed) and apply regulated 5V DC power through either the USB socket (CON2) or pin header (CON1). You should see the LEDs on the tree start to flash, although depending on the initial state of the shift registers, it may take 10-15 seconds before you see anything.

Hint: if you aren't using CON2, you can easily get the 5V DC required to feed to CON1 from the pins of a USB/serial adaptor plugged into a USB port.

If you don't have a *Christmas Tree* PCB, you can connect a simple LED in series with a 1kΩ series resistor across pins 2 and 3 of CON3, or even connect a piezo speaker (eg, Jaycar AB3440) to these pins (in this case, a faster clock rate is advised.

Alternatively, you can connect these devices to CON3, between either pin 1 or pin 2, and pin 3 (GND).

Further experimentation

Finally, if you want to see what makes the LFSR 'tick', JP1-JP4, CON5 and CON6 can be used to change the 'taps', ie, which shift register bits are combined to define the shift register's input state.

To do this, remove the shorting blocks from JP1-JP4 and use patch leads to connect the four outputs that you want to feed back from the terminals of CON5 to the pins of CON6 (the order doesn't matter).

If you want to use fewer than four inputs to the XOR gate, wire the unused pins of CON6 to either GND or +5V.

The taps we have used with JP1-JP4 inserted provide a so-called maximal-length sequence (65,535 steps for a 16-bit shift register), but there are other combinations of taps which also create a maximal length, as well as a number that are much shorter.

Also note that if Q15 (ie, the last bit of the shift register) is not fed into the XOR gate, then that will necessarily result in a shorter sequence.

The article at **http://bit.ly/pe-dec20-shift** has more information on the mathematical theory of linear feedback shift registers, and also how they are used in fields such as cryptography and digital communications.

As mentioned earlier, if used to drive the *LED Christmas Tree*, you can place LK1 in its alternative position to switch the circuit into chaser mode.

If you decide to adjust the operating frequency as described above, by varying the value of either the 470μF capacitor or nearby 1kΩ resistor, keep in mind that this resistor value can't go much below 470Ω due to the limited output current of IC4a.

So to increase the frequency, you're better off reducing the capacitor value (lower value capacitors are usually cheaper, too!).

You can increase the resistor value, so if you want to make the frequency variable, you could connect a 10kΩ potentiometer (or similar) in series with a 470Ω resistor between pins 1 and 2 of IC4a, then reduce the timing capacitor value to 4.7μF to give an adjustable frequency of around 2-40Hz.

If you reduce the timing capacitor to 33nF, that will give a clock rate of about 20kHz, and you will then get a signal that's suitable for basic audio use, as a white-noise source. But note that at this rate, it's hardly even a pseudo-random number generator: the sequence will repeat every few seconds, and that will be quite apparent.

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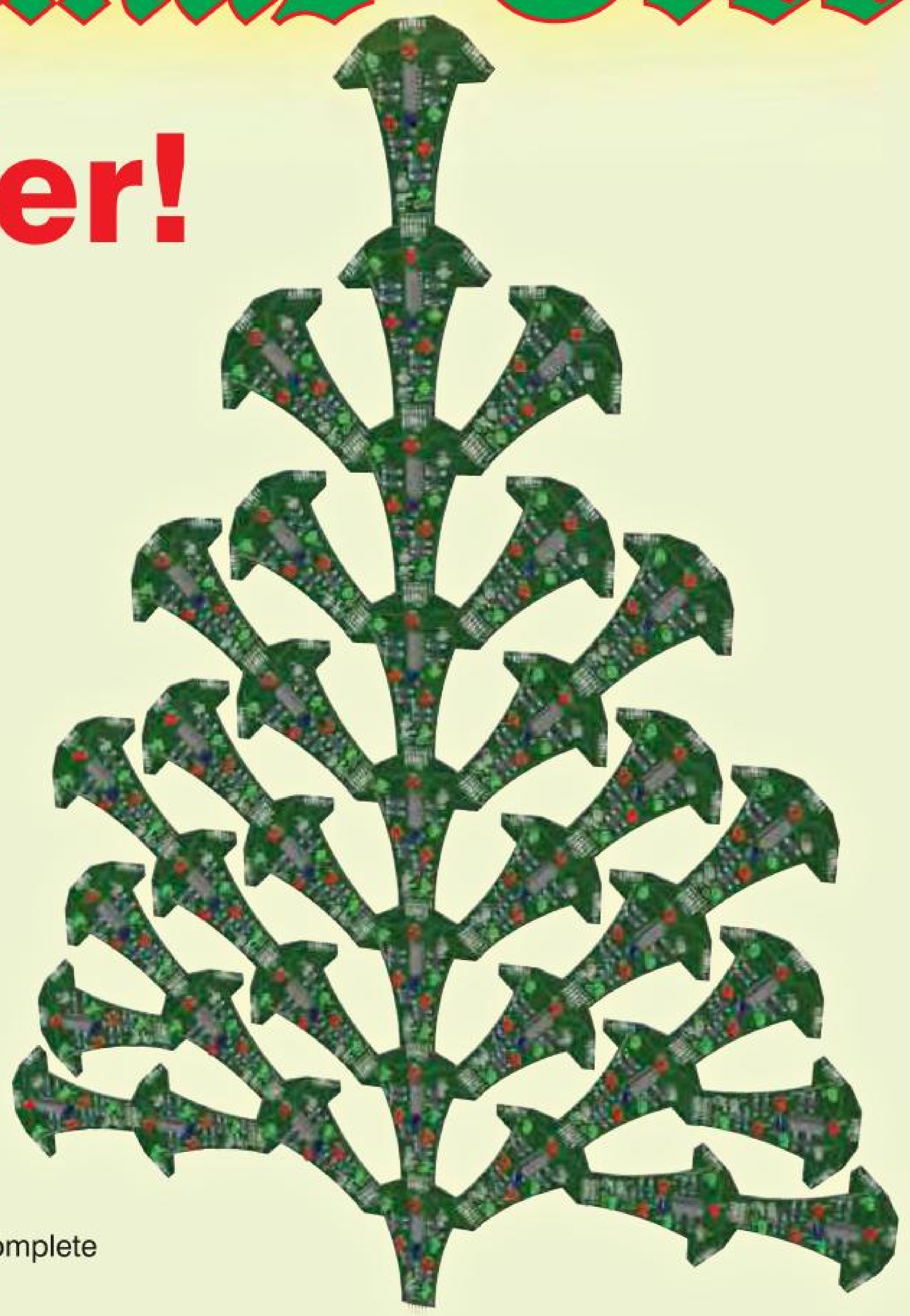
LED Christmas Tree

PCB special offer!



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Teach-In 8 CD-ROM Exploring the Arduino

This CD-ROM version of the exciting and popular *Teach-In 8* series has been designed for electronics enthusiasts who want to get to grips with the inexpensive, immensely popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. *Teach-In 8* provides a one-stop source of ideas and practical information.

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HIGH-POWER 45V/8A VARIABLE LINEAR SUPPLY

Over the last two issues, We described how our *45V/8A Linear Bench Supply* works and how to assemble its main PCB control module. Now it's time to finish it off. That involves cutting some holes in the case, mounting the components inside, attaching the front panel controls, wiring it up and the final calibration/testing.

SILICON CHIP
45V
8.0A
TRIP
SET: 45.8V 0.20A
20°C 45.8V 0.02A
LOAD ON
SET VOLTAGE
CURRENT
+
Variable DC Power Supply

Part 3

by Tim Blythman

We chose to put the Bench Supply in a Jaycar HB5556 instrument case because it's just big enough to fit everything without making it too large or heavy; it's reasonably priced and easy to get, easy to work and it has plenty of ventilation for the required cooling air.

The following instructions assume you are using that case. If using a different case, make sure that all the parts will fit inside and that nothing will foul anything else; if it's substantially larger, you should be fine.

You also need to ensure that it has adequate ventilation, especially in the top and bottom panels around where the heatsink will be mounted. Ambient air is sucked in through holes at the rear of the case, blown over the heatsink and exits through holes above and below the heatsink fins. Your case will need to have a similar arrangement.

It also needs to be made of steel or aluminium, not only for strength but also so that all of its panels can be earthed for safety.

Any case that meets these requirements can be used, but you will have to vary the instructions regarding where to mount the components inside the case and on the front and rear panels, and adjust the cutout and wiring placements to suit.

So without further ado, let's get to finishing off the *Bench Supply*.

Preparing the case

Several holes need to be drilled and cut into the metal instrument case. The front panel hosts the panel meter, control potentiometers, output binding posts, overcurrent LED and load switch, while the mains socket and fan cooling holes are on the rear panel. All six panels also have earth screws to ensure safety.

The bottom part of the case also needs to be drilled to mount the transformer, PCB and heatsink. The top and bottom panels are vented; the case is oriented with the vents at the rear, as this is where the fans and heatsink are mounted.

It may help you to start by putting the case together, so you understand how all the parts fit, then mark where holes will be drilled in each panel while it is in place.

Fig.8 shows the hole locations and sizes for the front and rear panels. We recommended in the article last month that you use the blank PCB and heatsink spacer to mark out the required hole locations in the base, as well as the hole for the transformer mounting bolt. Check now that these are in the right places.

The case is made of aluminium, so it is not hard to work. No holes need to be made in the case sides, but their internal ribs must be trimmed to allow all the components to fit. We recommend test-fitting all the parts before doing any drilling or cutting, to make sure it will all go together properly later. This is especially true if you are making any variations from our design.

Rear panel preparation

Even though the panels are not flat, they can be held in a vice by placing them between some scraps of timber. This will also help to prevent damage to the enamel finish.

We opened up the large holes in the panels using a 3mm drill bit on a drill press, making numerous closely-spaced holes inside the outline. The holes were then joined with a hacksaw, after which the edges were brought to dimension and finished with a file. You may also find a nibbler useful, if you have one that can handle 1mm thick aluminium.

For the hacksaw cuts, we removed the blade from the hacksaw, threaded it through the pilot hole, reattach the blade to the hacksaw and then made the panel interior cuts.

We suggest that you use a similar technique to make the cutout for the IEC socket. Mark its outline on the rear panel and then drill a series of small holes inside the perimeter. Keep the holes well inside the markings.

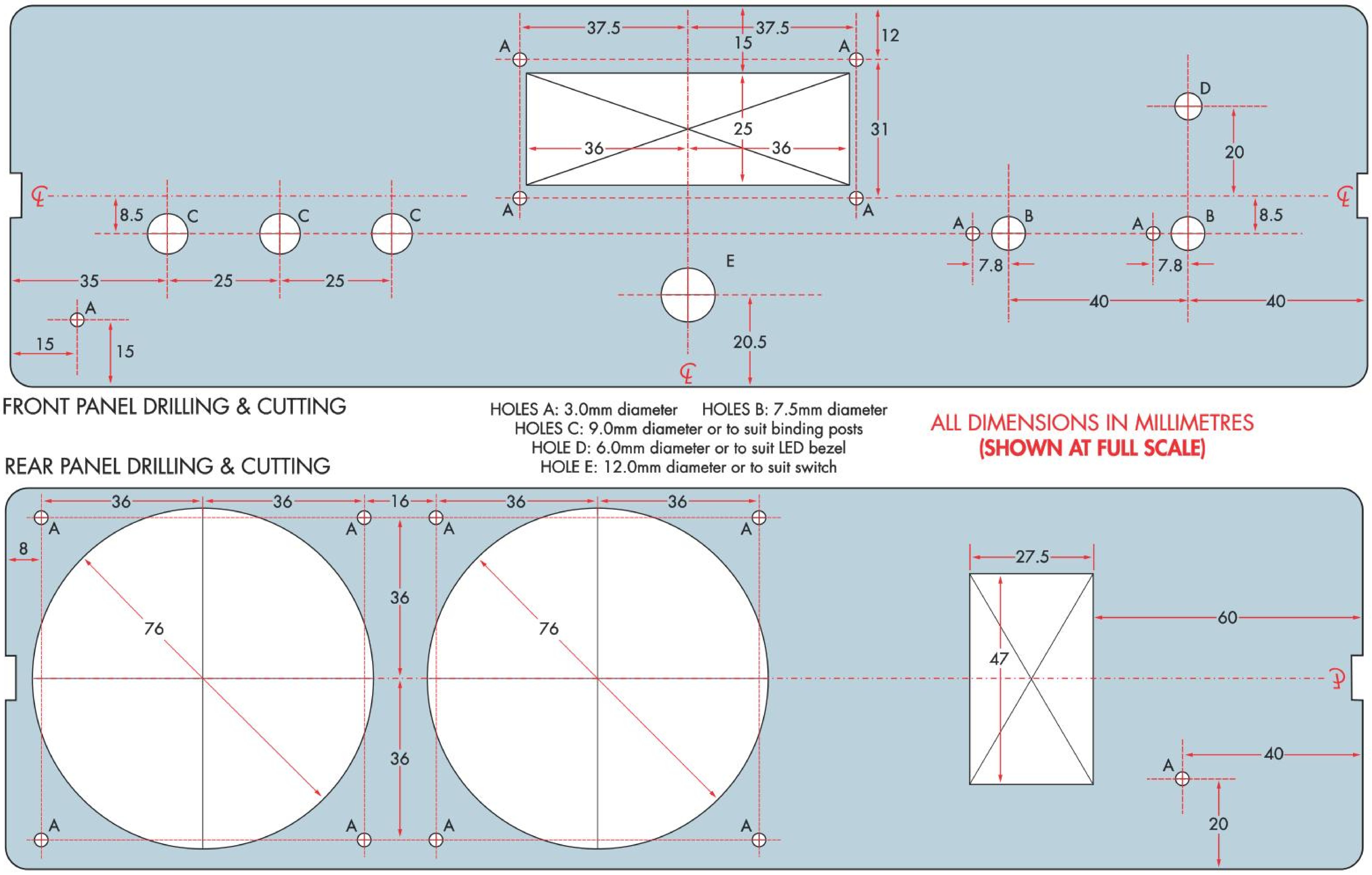

FRONT PANEL DRILLING & CUTTING
REAR PANEL DRILLING & CUTTING
HOLES A: 3.0mm diameter
HOLES B: 7.5mm diameter
HOLES C: 9.0mm diameter or to suit binding posts
HOLE D: 6.0mm diameter or to suit LED bezel
HOLE E: 12.0mm diameter or to suit switch
ALL DIMENSIONS IN MILLIMETRES
(SHOWN AT FULL SCALE)
A
B
C
D
E
37.5
12
15
25
36
31
20
8.5
7.8
35
40
20.5
16
8
76
27.5
47
60

Fig.8: these are the cutting and drilling diagrams for the front / rear panels. Note they are 60% of life size, so to copy and use as a template you will need to enlarge them by 166.7%; or download them as PDFs from the December 2020 page of the *PE* website.

Drill a larger hole (large enough for a hacksaw blade or other small metal saw) inside. Then use a hacksaw blade to cut towards the corners from the large hole in the centre.

Take care that the sheet metal does not bend and break on the forward stroke. Once the cuts have reached the corners, the triangular shapes may be flexed along the drill holes, to break them off.

Use a file to carefully bring the edges of the cut to their correct dimensions. Keep the mains socket nearby to test fit, as you do not want to take away too much metal. This could cause the receptacle to be not held securely by its tabs.

Try fitting the socket at an angle to test the height and width independently. Once the dimensions are correct, gently run a file across any sharp edges of the opening to remove any burrs.

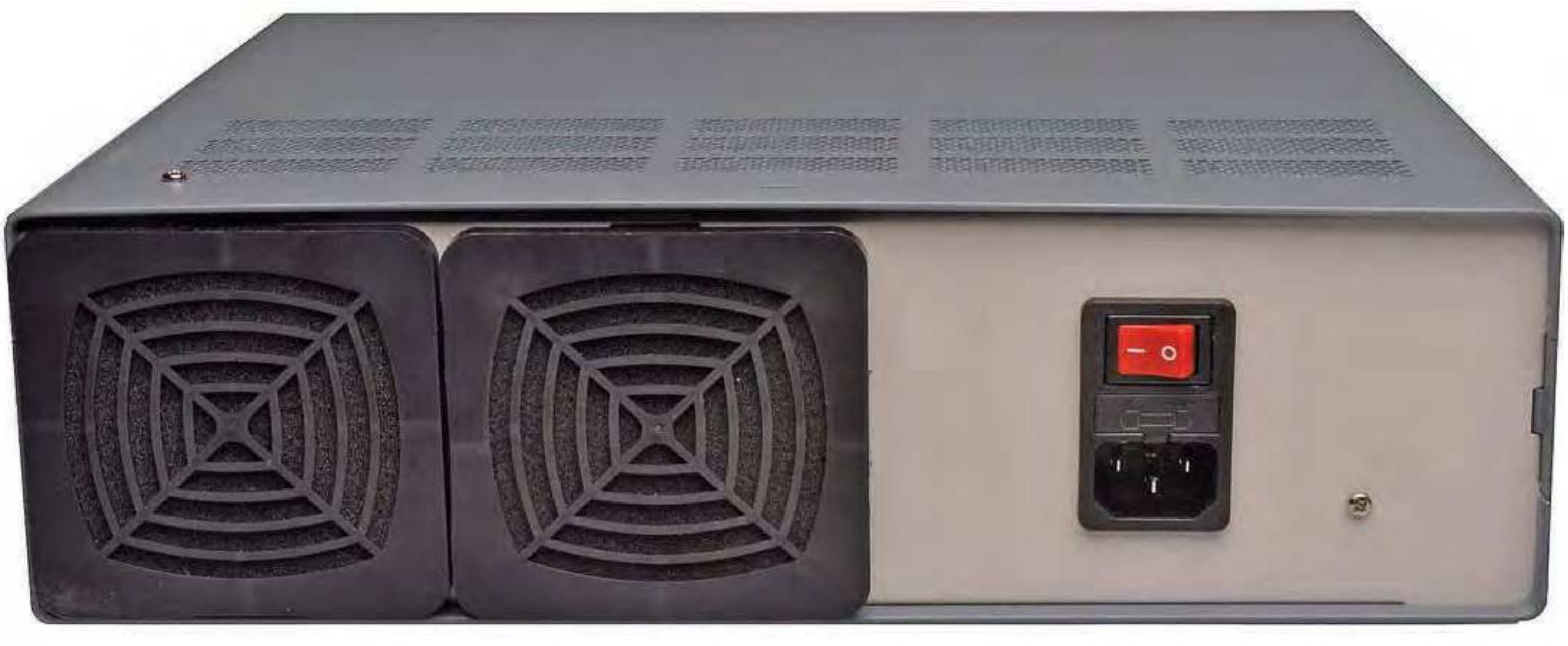
Now is a good time to drill a 3mm hole in the rear panel for the earth connection. The location is not critical, but placing it near the receptacle minimises the earth wire length. Sand the inside of the panel until you have an area of exposed bare metal 1cm in diameter around the hole.

The aim is to make a good metal-to-metal connection with the eyelet lug at the end of the earth wire.

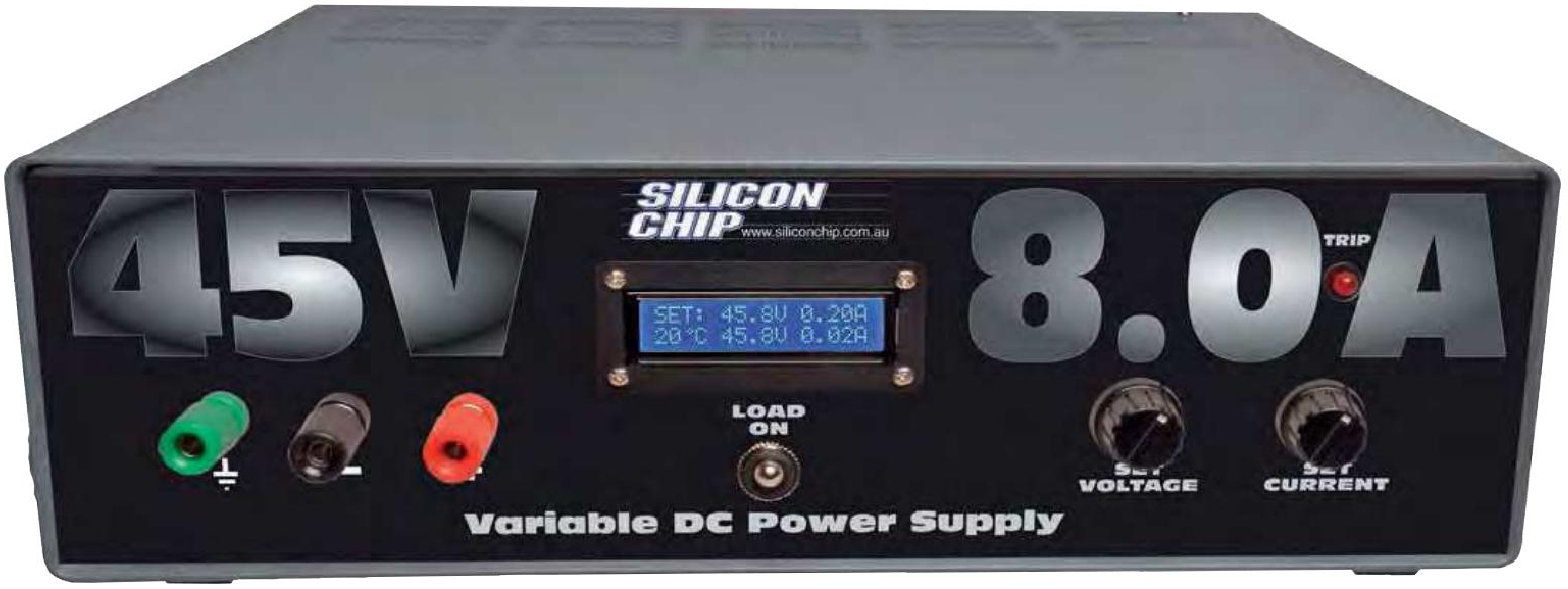
You will also need to drill eight 3mm holes to mount the fans. Test fit the fans to check their locations as there is not much room around the fan guards, and they need a small amount of clearance to allow the filters to be clipped on and off.

You may need to space the fan mounts so that they aren't hard against each other.

Two large holes are required so air can be drawn in by the fans. We traced out a circle using the inside of the fans as a



There isn't much mounted on the rear panel; just the switched, fused IEC mains input socket and the two cooling fans. The small screw head visible to the right of the mains socket is the main earth point inside (see photo on page 39).



The front panel of the *Bench Supply* has two knobs to set voltage and current and a switch to connect or disconnect the load, along with the three output terminals. The red LED above the current knob indicates when thermal limiting is occurring. The LCD screen shows the actual and set voltages, actual current and current limit, plus the heatsink temperature.

template, but any circular object around 80mm across will be fine (or copy/print Fig.8 to use as a template). Check that the fan guards completely cover your marked hole before cutting it out.

Use a similar technique to the IEC receptacle to open out the holes. Drill a series of small holes and then open up the panel with a hacksaw blade and finish by filing down the rough edges.

You can now fit the mains socket. Orient it so that the lead plugs in below the switch, allowing access to the switch from above. Now is also a good time to insert the fuse.

While the 6A fuse chosen may seem excessive for a 500W transformer, this is the recommended rating for that transformer. Lower-rated fuses will blow due to inrush current when the unit is switched on.

If you want to use a lower-value fuse, it will need to be a slow-blow type.

Front panel preparation

The front panel is treated similarly to the back. Assuming you are using our *Five-way Panel Meter*, check that your LCD screen's dimensions match our template and then transfer this to the front panel. We have designed an acrylic bezel that suits the LCD on the *Five-way Panel Meter*, which hides any small inaccuracies in cutting the front panel around the meter.

You can place the bezel over the LCD to see if it matches the dimensions and if so, use it as a template to mark out the front panel. Otherwise, use the LCD dimensions or Fig.8 as your guide.

If you have separate panel meters, check their specifications for recommended cutout dimensions, and plan how they should be laid out, leaving room for the binding posts, switch and the potentiometers.

Cut out the opening for the panel meter(s) using the same technique as for the mains socket. Don't forget you need to drill the four 3mm mounting holes.

You also need to drill two or three holes for the binding posts; three are required if you want an earth post, which can come in handy from time to time. Otherwise, the supply outputs are 'floating'. Check the diameter of the holes required for your posts and drill them with equal spacings. Ours were 9mm.

Start these holes by using a punch to locate the centre of the hole and then by drilling with a smaller size to create a pilot hole. Finish with the recommended size drill bit to complete the hole.

Similarly, drill a hole below the panel meter for the output on/off (load) switch. Typical panel-mount toggle switches require a 6.5mm hole, but again, it's best to start with a smaller pilot hole and then enlarge it to the final size before deburring.

Below the banana socket holes, add a 3mm hole for the front panel earth. As for the rear panel, sand the inside to remove enamel for about 1cm around it.

The two potentiometers require two holes each to mount; one for the shaft and a second to hold the locating lug so that the pot won't rotate. Drill the two holes using the usual technique.

Drill a hole for LED1 as well, taking into account the bezel diameter.

If you wish to add our front panel artwork, you should do so now. You can download it as a PDF from the December 2020 page of the *PE* website; then print it out and laminate it. Note that the front panel is wider than an A4 piece of paper is long, so it will look better printed on A3 so that no joins are needed.

Mounting the front panel components

Solder a 20cm length of black 10A-rated wire to the black binding post, and a 20cm length of red 10A-rated wire to one terminal of the output switch. A second 5cm length of red wire is then soldered between the other switch terminal and the red binding post.

Insulate the solder joints with heat-shrink tubing. Strip back the last 5mm of both free wires for connecting to CON1 on the main PCB.

If adding an earth binding post, attach a short length of 10A green/yellow wire stripped from mains flex or a mains cord, and crimp or solder an eyelet (ring) lug to the other end. It will attach to the front panel earth screw later.

The binding posts and output switch can now be secured using the supplied nuts and washers. Orient the switch so that it makes the connection from the red binding post to CON1 + on the PCB when it's down (the standard position for 'on' in Australia and New Zealand).

Thread the potentiometer shafts through the panel from the back and locate the lugs into the smaller holes to stop the potentiometers from rotating. Secure at the front with mounting nuts and fit the knobs.

We used spline shaft potentiometers, which allow the knobs to be attached at almost any angle. If you have D-shaft potentiometers, you may need to rotate the front part of the knob later so that the pointer sweeps over an appropriate range (these can usually be prised off with a knife).

Now mount the rest of the front panel hardware. Fit the LCD bezel by threading a 12mm M3 machine screw through each corner, then feed the screws through the holes in the front panel. Secure with M3 nuts at the back of the panel.

If your LCD has mounting holes which are too small to fit an M3 screw, these can be carefully enlarged with a 3mm drill bit, ideally in a drill press. *Avoid inhaling the fibreglass dust which results.*

The *Five-way Panel Meter* LCD can then be threaded over the back of the machine screws and held in place by four more nuts. Attach the IDC cable to the header, ensuring the marked pin 1 on the cable lines up with that on the PCB.

Finish by pushing the LED with bezel through the hole you drilled for it earlier.

Transformer and main PCB

If you haven't already marked out and drilled the required holes in the bottom of the case, use the populated PCB, heatsink spacer and transformer to determine where the holes need to go. All of these need to be drilled to 3mm and deburred, except for the transformer-mounting bolt hole which will need to be larger. Measure the diameter of the supplied bolt; around 8mm should do.

Before drilling those holes, it's a good idea to slot the front and rear panels into the case to make sure that the internal components will not foul anything mounted on either panel. Test fit the transformer and PCB according to the markings, to ensure that everything fits as expected, then drill the holes.

You may need to remove the side panels as they are likely to conflict with the PCB and transformer mounting positions. You can test fit these later to confirm how they need to be trimmed. We needed to trim away some of the internal parts of both side panels on our prototypes, as the side panels protrude slightly into the case near their fastening holes and screws.

Check that there are no collisions between the PCB, transformer and front and rear panel hardware. Keep in mind that the fans and their spacers will sit between the heatsink and the rear panel. You might also like to check that the transformer's leads reach the mains plug receptacle and the bridge rectifier tabs on the PCB.

If everything appears correct, then drill the holes in the base. The smaller holes for the PCB and heatsink that sit in the vented region of the base can be tricky to drill, but if they end up slightly out of the marked positions, that should not be a big problem. In the worst case, you will just have to enlarge these holes slightly.

Also drill a 3mm hole for the mains earth in the base. Place it near the mains receptacle, but clear of the vented region. As with the other earth holes, sand the area around it to expose the underlying metal.

The transformer is quite heavy so take care not to drop it while working with it. Feed the bolt through the bottom of the case, then place one of the rubber gaskets over its shaft on the inside. Lower the transformer into place, rotating it so that the wires are close to where they need to connect.

The second rubber gasket goes on top of the transformer, followed by the dished metal plate with its convex side facing down. Slide the small washer in place, thread the nut onto the bolt and tighten it up to a reasonable degree, so the transformer is held securely in place. Do not overtighten it or you could damage the transformer windings.

Remove the two 9mm tapped spacers from the PCB that are nearest to the heatsink. Alternatively, if you haven't already fitted them, fit the two spacers furthest from the heatsink but leave the other two off.

Getting the PCB into position in the case can be tricky due to the weight of the transformer. We found that it was possible to balance the case on its edge by using the weight of the transformer to hold it upright.

Start by feeding one M3 × 10mm nylon machine screw through the base of the case and into the heatsink, making sure to thread it through the acrylic spacer. Then fit the other three nylon machine screws to hold the heatsink in place. This should also hold the PCB in place, for now. Metal screws cannot be used on the heatsink as this would connect the live heatsink to earth.

Use two machine screws to secure the front of the PCB to the bottom of the case.

Now is a good time to attach the feet to the case. We used taller feet than those included with the enclosure, as those were so short that the transformer mounting bolt head was still touching the bench with them in place. Taller feet also provide more space for cooling air to escape via the underside vents.

The main requirement for the SPST 'LOAD' switch (mounted under the display) is that it must be capable of handling the whole output current – up to 8A DC. Practically, this means you'll need a 10A *DC* switch – don't be tempted to use one only rated for 10A *AC* – it's not enough!

Rear panel and fan mounting

The fans can now be fitted. They are mounted to the rear panel on spacers. Ideally, they should be as close as possible to the heatsink, but not touching.

Take one fan and thread four 32mm machine screws through the corner holes. Fasten them to the fan using the 15mm-long M3 tapped spacers. These will sit against the rear panel, so if there is room to bring the fans closer to the heatsink, nuts or washers can be placed under the spacers.

Just make sure that the fans don't touch the heatsink fins.

Now separate the fan filters/guards into two pieces and place the fans on the inside of the rear panel and the guards on the outside. Attach the fans using 9mm-long M3 machine screws through the guards and rear panel, and into the tapped spacers attached to the fans.

Clip the fan filters back into place on the guard frames.

With the PCB and transformer in place, you can mark and cut the required cutouts in the side panels, to clear the internal components.

You can see how much material we had to remove in our photos. There is a fair degree of overlap between side, top and bottom panels, so slight inaccuracies in cutting the side panels will be hidden.

Firmly hold the side panel in a vice using timber off-cuts to protect the finish. Make the marked cuts with a hacksaw. If the panel vibrates as you saw, try clamping it closer to where the cut is being made.

Check that the panels now clear the transformer, PCB and heatsink. Once everything fits together correctly, dress any sharp edges of the side panels with a file.

The side and top panels will also need to be earthed. This can be done via the remaining sections of the mounting tabs. These are already slotted, so you don't need to drill any holes. Just remove the enamel from a small area on one of these tabs, where the earth eyelet will be attached later (see photo on page 38).

Use an area near the back of the side panels, as the earths will all connect back to the rear panel.

For the top panel, choose a location opposite the earthing location on the bottom panel, which is otherwise clear of components. Drill a 3mm hole and sand the inside of the panel as for the others.

Making the final connections

The leads to the fans, LED, panel meters and thermistor can be plugged into their respective board connections. The leads for the banana sockets screw into terminal block CON1.

Ensure that they are connected with the correct polarity, ie, red wire to the '+' terminal.

Mains wiring

The transformer needs to have spade crimp lugs fitted to mate up with the IEC plug receptacle and bridge rectifier. The transformer we used has two 115V AC primary windings, which are intended to be connected in parallel for 110-120V AC mains and in series for 220-240V AC mains.

The secondary windings are 40V AC each, and in this application, they need to be wired in parallel.

Also, the integral DPST switch in the IEC input socket is not joined internally to mains live or to the fuse. Instead, it has separate spade lugs to make connections. So we will need two short leads, one brown and one blue, to make these connections.

Ensure there's no chance that a mains cord can be plugged in while you are working on the mains side of the circuit.

Cut a 100mm length of brown wire and another 100mm length of blue wire, stripped from 10A-rated mains flex or a spare 10A mains cord. Strip both ends of both wires and securely crimp spade lugs onto them. Insulate the exposed metal using heatshrink tubing.

Once you've made up those two wires, plug them into the rear of the IEC socket, with one going from the fused live terminal to one pole of the switch and the other going from the incoming neutral lug to the other pole of the switch.

Do not connect them both to the same switch pole!

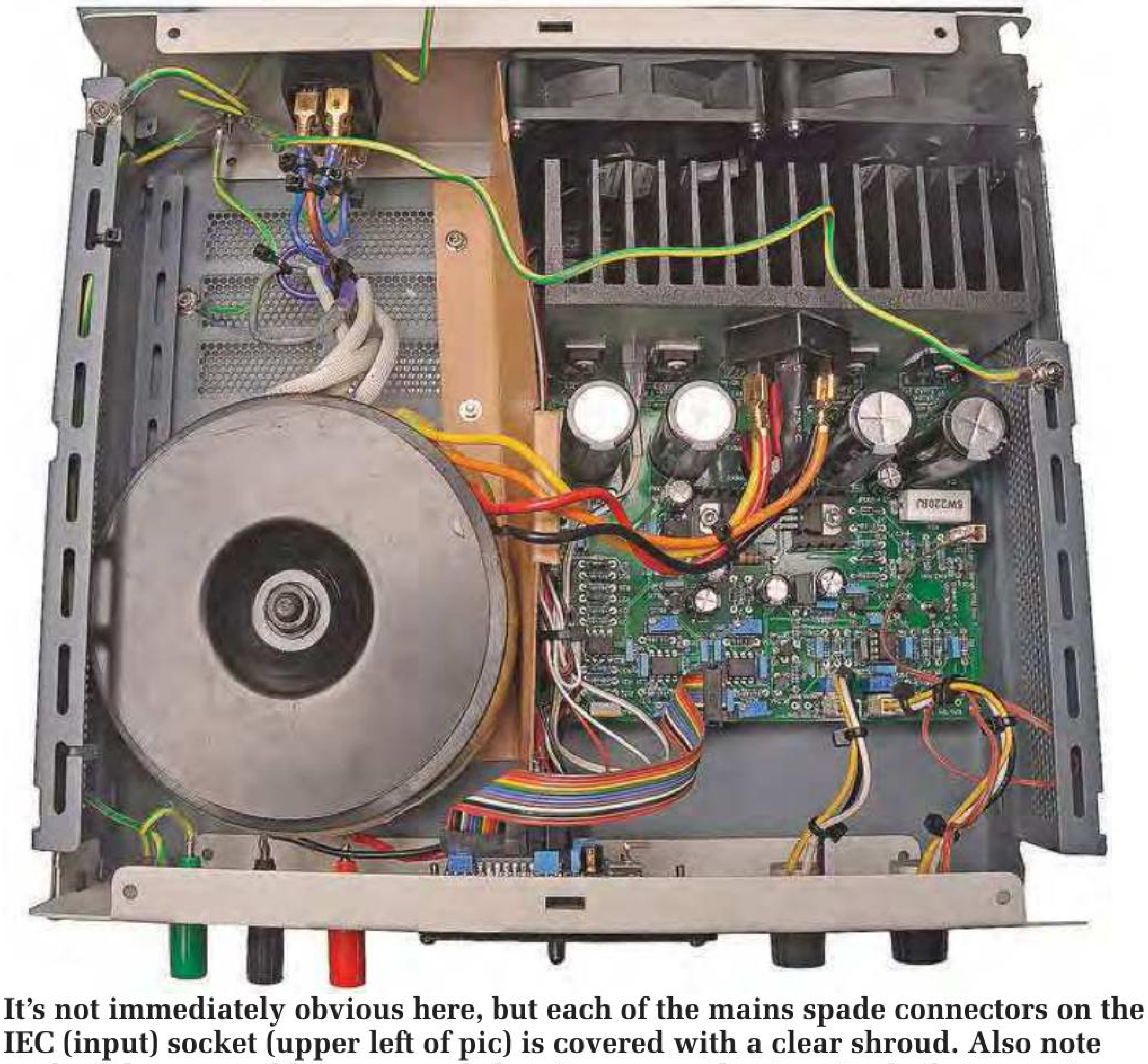
Now is also a good time to insulate the exposed metal strip on the back of the IEC socket using neutral-cure silicone sealant, to make working on the inside of the *Bench Supply* a bit safer.

To wire the transformer primaries in series, solder the grey wire to the purple wire and cover the joint using two layers of heatshrink tubing. Remember to slip the tubing over the wires before soldering them.

If you are using a different transformer than the one we specified, check the manufacturer's instructions for wiring it up to a 230V AC supply.

Next, fit spade connectors to the transformer's brown and blue (primary) wires and insulate them with heatshrink tubing. Push these onto the two remaining switch terminals on the mains socket, so that the wires going to the two switch poles match (ie, brown/brown and blue/blue).

It's essential that you now use multiple cable ties to tie all the mains wiring around the IEC input socket together, so that if any of the wires come loose, they won't flap around the case and potentially make contact with the heatsink, PCB or any other non-mains conductors.



It's not immediately obvious here, but each of the mains spade connectors on the IEC (input) socket (upper left of pic) is covered with a clear shroud. Also note each of the removable case panels has its own earth wire attached, connecting back to the main earth point on the rear panel (alongside the IEC socket).

The two 80mm fans we used were specifically chosen for their high flow rate. They're Digikey P122256 24V models, available from digikey.com
If you substitute other fans they may not have the essential cooling properties of these ones.

You will also need to fit a Presspahn insulating barrier alongside the heatsink and PCB, so that if a mains wire does somehow come loose, it cannot come in contact with those parts. Cut the sheet of Presspahn to 105 × 208mm and score it 20mm in from one long edge, making a 208 × 20mm foldable section.

Now fold that part by 90°, place it in the case alongside the heatsink and drill two holes in the base, through the bottom of the case, close to each end. Attach it to the case using 6mm M3 machine screws and nuts.

The photo opposite shows what it will look like when you've finished. This piece will come close to touching the lid when it's attached forming an insulation barrier between the heatsink/PCB and the mains wiring.

You will need to use side cutter to make two cuts along the top edge and fold it down, for the transformer secondary wires to pass through. Again, see the photo for an idea of how this was done on our prototype.

Earth wires

The next step is to make and fit the panel earths. Five green/yellow wires are required with eyelet connectors crimped to each end. These will go from the rear panel earth screw to the other panels. A sixth wire is needed, with a spade lug at one end (to suit the mains socket) and an eyelet at the other, to go to the rear panel star earth point. None of the crimp connections need to be insulated.

Cut the earth leads to length, giving enough slack so that you can pull the panels apart later, and so that they can avoid any components which might be in the way. The lead for the top panel should have more slack than the others, as it will need to allow the top panel to be detached and moved out of the way while still being connected to earth.

Once the wires have been made up, plug the spade terminal onto the earth terminal of the mains socket. Thread a 12mm M3 machine screw through the rear panel hole, then place a star washer over the screw shaft, followed by the six earth wire eyelets.

Secure with an M3 hex nut and tighten well. Then add another nut on top, doing it up moderately tight, to act as a locknut.

Now terminate the other end of the five remaining earth leads to the five other panels similarly. The screw heads should be on the outside of the case, with the eyelet connected to each panel through the star washer, with the screw held in place by a nut done up tightly. The front earth binding post (if fitted) should have its eyelet placed on top of the front panel earthing eyelet.

The final connections to be made are from the transformer secondaries to the bridge rectifier (BR1) on the heatsink. To parallel the secondaries, solder or crimp the orange and black wires into a spade together and insulate it with heatshrink tubing. Do the same with the yellow and red wires, into a second spade lug.

Again, if you are using a different transformer, you should check this configuration as it may be different.

Plug the two spades on the AC lugs on the bridge rectifier. Check that everything else has now been connected

Final assembly

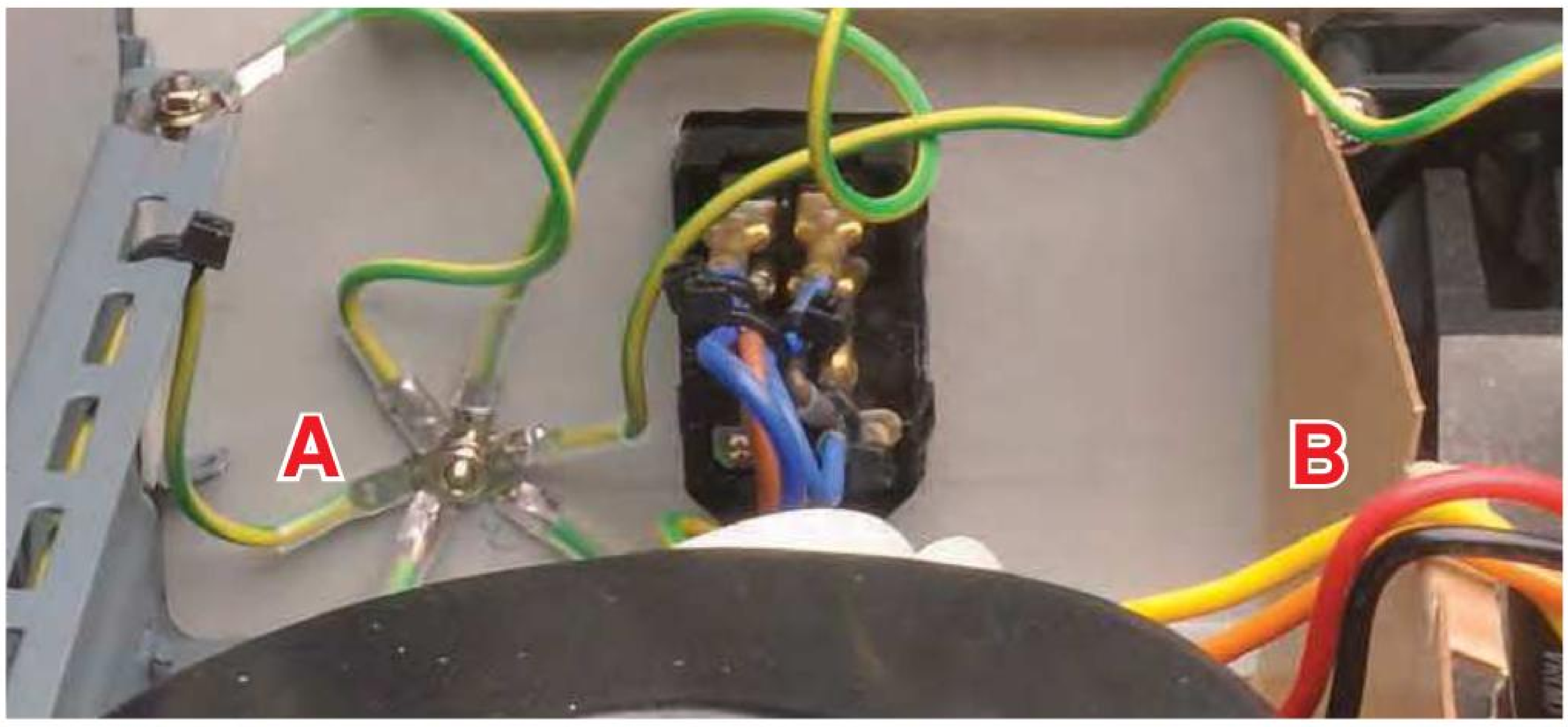
The back, front and sides of this case can be tricky to assemble. You might find it easier to join the front, back and sides together as a unit and then slot this onto the bottom panel. Screw two of the panel screws into the sides, securing them (and thus the front and rear panels) to the bottom.

Check that these screws do not foul the transformer or PCB as you do this. They are much longer than necessary, so can be trimmed, if it comes to that.

You can test fit the case lid as well. It should slot onto the remainder of the case, with the last two screws used to secure it. But leave it loose for now, as we will need access to the PCB for the final tests and calibration.

Now is a good time to tidy up the wiring. Use cable ties to secure the wires into neat bundles (you should have already tied the mains wiring together).

The slotted ribs on the side panels are great places for attaching the cable ties, holding the wire bundles out of the way. This is also a good chance to run your eye over everything and make sure you can't spot any wiring or construction problems.



A close-up of the rear of the *Bench Supply* showing (A) the main earthing point and (B) the Presspahn insulation forming a barrier between the high and low-voltage sections. Don't leave these out: they're for your safety!

Final testing

Ensure nothing is connected to the supply outputs and that the front panel knobs are fully wound down to their minimums.

Connect mains power and switch the unit on via the rear panel switch, keeping yourself well clear of all the internals. It's best to leave the wall socket switch off, ensure the IEC input socket switch is on, then stay clear of the unit while switching it on at the wall.

The front panel meters should light up and should all have readings close to zero; if they do not, power off and check for problems. The temperature reading on the *Five-way Panel Meter* should be around ambient.

If the temperature is above 20°C, then the fans may start up. Connect a multimeter on its volts range to the output terminals, with the output switch on (down). The reading should be 0V. If not, shut down and check for faults.

If all is well, turn up the current limit pot to slightly above zero, maybe to around one-tenth of its range. At the zero position, the output is completely inhibited.

Slowly advance the voltage pot; you should see the voltages on the meter rise. If this is the case, then we can calibrate the voltage display. Dial up the voltage until you get 50V DC across the output terminals. If it does not reach 50V at its maximum, adjust VR1 to allow this.

Now adjust VR5 and VR6 until their respective meters (set voltage and actual voltage) are both showing 50V. This will probably be at around a third of their range from the minimum position.

So far, all the work is being done by REG3. We will now test that the *Bench Supply* will hand off to the current-boosting transistors at higher currents. Dial the voltage pot down to the minimum and connect a 1kΩ resistor (1/2W is fine) across the output binding posts.

Now dial the voltage up to 20V; this will be just below the power limit of a 1/2W 1kΩ resistor. Check the voltage across the 68Ω resistor near REG3. It should give a reading of around 0.6V, the base-emitter switch-on voltage of transistor Q3.

If the reading is above 1V, then REG3 is passing all the current, and the transistors are not taking the load. Power off the unit, give it a minute for the capacitors to discharge and check for problems around the heatsink-mounted transistors.

Assuming all is well, dial the voltage and current down and remove the 1kΩ resistor.

We can now calibrate the current meters. You can connect an ammeter (or multimeter at 10A setting) directly across the outputs, although this will involve running the PSU at maximum dissipation. It is a good idea to connect a high-power series load resistor if you have one.

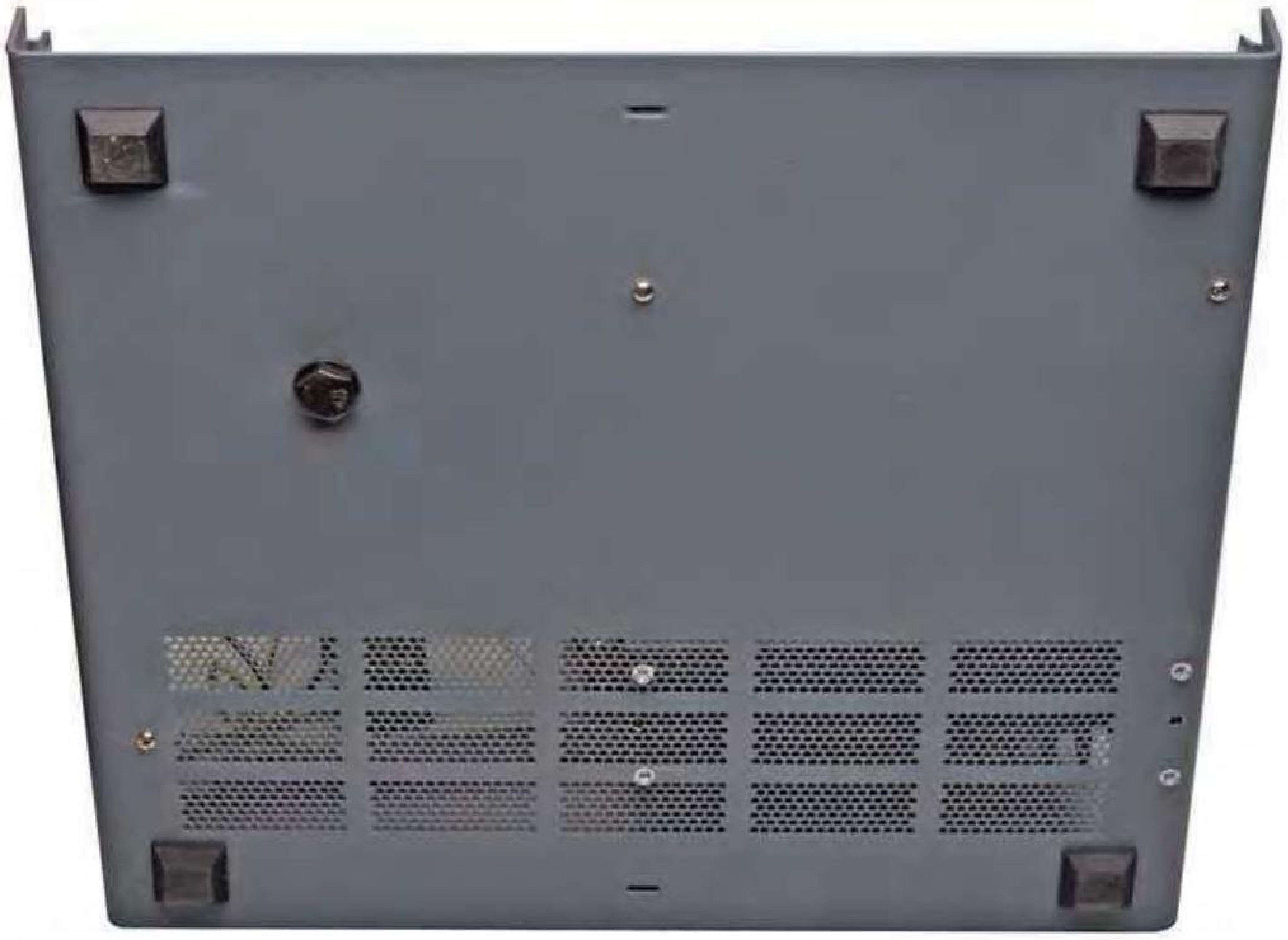
We want the *Bench Supply* to be delivering 8A to provide the best calibration. Dial up the voltage slowly; if you only have an ammeter connected across the outputs, you should not see a voltage reading much higher than 1V (depending on lead and load resistance).

If it goes much higher, that suggests that there is a problem with the current limiting. The voltage will be higher if you have a series resistor connected.

As you advance the current-limit pot, assuming the set voltage does not match the actual voltage, that means that current limiting is occurring. The fans should start running if they are not already.

Continue winding it up until the meter shows 8A. If it does not reach 8A, then adjust VR2 to fine-tune the maximum current limit.

Now adjust VR7 and VR8 until the *Five-way Panel Meter* (or your individual panel meters) show 8A for both the



The underside of the *Power Supply* case, showing the locations of the holes required for the transformer (the big black bolt), the heatsink (nylon screws on/near ventilation holes) and the PCB mounting pillars (right side of pic) The single screw on the left side is for the case earth. All holes are 3mm with the exception of the transformer mounting (we used an 8mm bolt).

set current and actual current. These pots will need to be wound to around 2/3 of their range from the minimum.

At this stage, the *Bench Supply* will be dissipating close to 400W, so the temperature will be steadily rising and the fans will be working harder as it does. You can use a contactless (IR) thermometer to check the heatsink temperature, which should be close to what's shown on the *Panel Meter*.

If you leave the current set to 8A, you can test the thermal limiting. When the temperature reading gets to around 80°C, the limiting LED should come on, and the current will drop. You may also hear the fans run a bit harder too. This is not a 'boost' mode, just the effect of the sagging DC voltage disappearing as the load is reduced.

If the temperature keeps rising past 80°C with no change in the output current, then shut the *Bench Supply* down and check for faults in that part of the circuit.

If it does enter limiting, then the *Bench Supply* is working as designed. Dial the current and voltage down to their minimums and let the fans run for a moment so that the heatsink cools down, then turn it off and disconnect your test load.

Finishing up

Now that everything is functional, it's just a matter of a few finishing touches. Secure any loose wiring with the cable ties. The wires on our transformer were not too long, so they did not need to be fixed to anything.

If yours are significantly longer, you can use self-adhesive plastic cable clamps to tidy them up.

The fan and thermistor wires can be bundled together and fixed against the right-hand side panel with adhesive wire clips. Similarly, the output wires to the binding posts should be attached to the base of the case with adhesive wire clips.

The other wires to the front panel can be bundled together with cable ties. Since they do not travel far, they should not need to be secured to anything else.

The earth wires should be clipped in place if there are any that might move around excessively. Take care with the lead for the top of the case if it has a lot of slack. You could fit a cable clip to the inside of the top of the case to secure it.

Secure the top panel in place with the two supplied screws. The *High Power Linear Bench Supply* is now complete.

Variations

While we aimed for 50V output voltage in our design, necessitating the 57V rail, you can use a lower-voltage transformer too. As long as the 24V regulator can still deliver 24V, the *Bench Supply* will still work.

To use a lower-voltage transformer, you may need to reduce the value of the 220Ω 5W resistor, to ensure the input of REG1 always stays above 26V.

You can also adjust the upper output-voltage limit downwards using VR1. VR1 may even need to be increased in value (eg, to 20kΩ or 50kΩ) if a very low output voltage is desired.

The current capacity of the output transistors is much higher than the 2A each we have chosen, but thermal considerations limit their operation. You could tweak the PSU to provide a higher output current if the input voltage (and thus total dissipation at zero output voltage and maximum current) is reduced.

The PCB tracks, CON6 and the wiring can handle up to 10A, so this is about the practical limit without making major changes. Note that you may need to reduce the value of the 27kΩ resistor in series with trimpot VR2 to set the current limit to 10A.

Fan considerations

We chose a particularly high-powered pair of fans to ensure that the output transistors will be cooled as much as possible. The 33Ω series resistor is suitable for these fans, but may not drop enough volts if different fans are used, particularly those with a lower current draw.

Its value should be chosen to provide a 9V drop (from 57V to 48V) at the typical current draw of the chosen fans. A 5W resistor should be suitable for up to around 500mA under these conditions.

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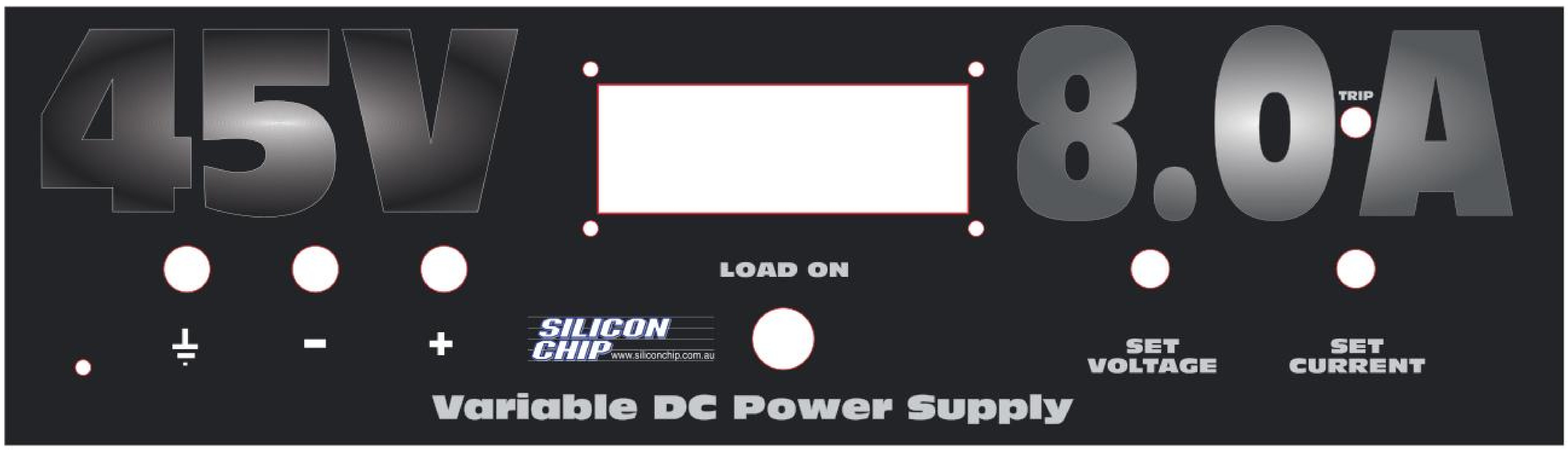


Fig.9: this front-panel artwork is shown here at 50% life size. The full-size version can be downloaded from the December 2020 page of the *PE* website.

Building a Hi-Fi amp on the cheap

by Julian Edgar

How do you build a great amp on a low budget? Using a salvaged amplifier as the starting point lowers costs a lot – so, rather than developing an audio amplifier from scratch, this article assumes that you are going to use either prebuilt or kit amplifier modules. Available amplifier modules span quite a range – you can choose from cheap and nasty, to low cost and very good, to high cost and excellent!

Building your own quality Hi-Fi amplifier sounds like a great idea, but there's a problem – these days, the costs add up so quickly. A good quality case – £50. Power transformer – £50. Rectifier/smoothing capacitors – £25. Heatsinks – £50. Amplifier modules – £75. We haven't even included hardware like switches, sockets and nuts and bolts yet, but suddenly you're into the cost realm of quite good commercial amplifiers – and with those, all you do is hand over the money… no construction needed!

But there is a solution at hand – start with a good quality salvaged amplifier. At minimum you'll get the case, heatsinks and a lot of hardware. And at maximum? The power supply transformer, rectifiers and filter capacitors.

Suddenly, creating a new, quality audio amplifier can be as simple as installing some new pre-built or kit amplifier modules!

Starting points

There are two directions from which you can begin – and the first is to start with the main power supply transformer in the salvaged amplifier. Audio amplifiers typically require positive and negative supply rails, achieved by using a centre-tapped transformer followed by a rectifier and filter capacitors (these latter parts are easily achieved by again buying an off-the-shelf module).

If the discarded amplifier has a good quality transformer (eg, a large toroidal design), measure its AC outputs. Depending on the amplifier, the transformer output might be anywhere in the range from 18V to 43V per winding – or more.

The power capability of the transformer can be measured by adding loads (eg, high-power resistors or incandescent light bulbs) and monitoring the voltage sag. Most transformers are specified for their rated current at a 10% voltage drop. However, rather than making measurements, it's often easier to just guess the VA rating of the transformer based on its size. For example, a 300VA toroidal will usually be about 110-120mm in diameter and about 50mm high, while a 500VA toroidal will be similar in diameter but about 65mm high. If in doubt, look at a few online catalogues, the physics of transformers means that sizes are pretty consistent. In rare cases, the VA rating of the transformer will be written on it.

With the transformer specs available, you then have a starting point from which you can select suitable amplifier modules – either kit or prebuilt.

For example, the very well regarded SC200 amplifier kit mono module (see *PE*, January to March 2018) requires a 40-0-40V transformer. At the other end of the pricing spectrum (and probably also audio quality spectrum – all things are relative!) is the two-channel 300W amplifier board (available from Banggood – model V-MOS300W) that requires a 24-0-24V transformer. This module has a built-in power supply, so no further electronics are needed – just speaker and input connections. (But you would probably also want to upgrade the provided heatsink.)

PE audio guru Jake Rothman suggests a good rule of thumb is to select a transformer with a VA rating double the audio power rating of the amplifier. That is, a 150W (total) amplifier would require a 300VA transformer. Obviously, the exact

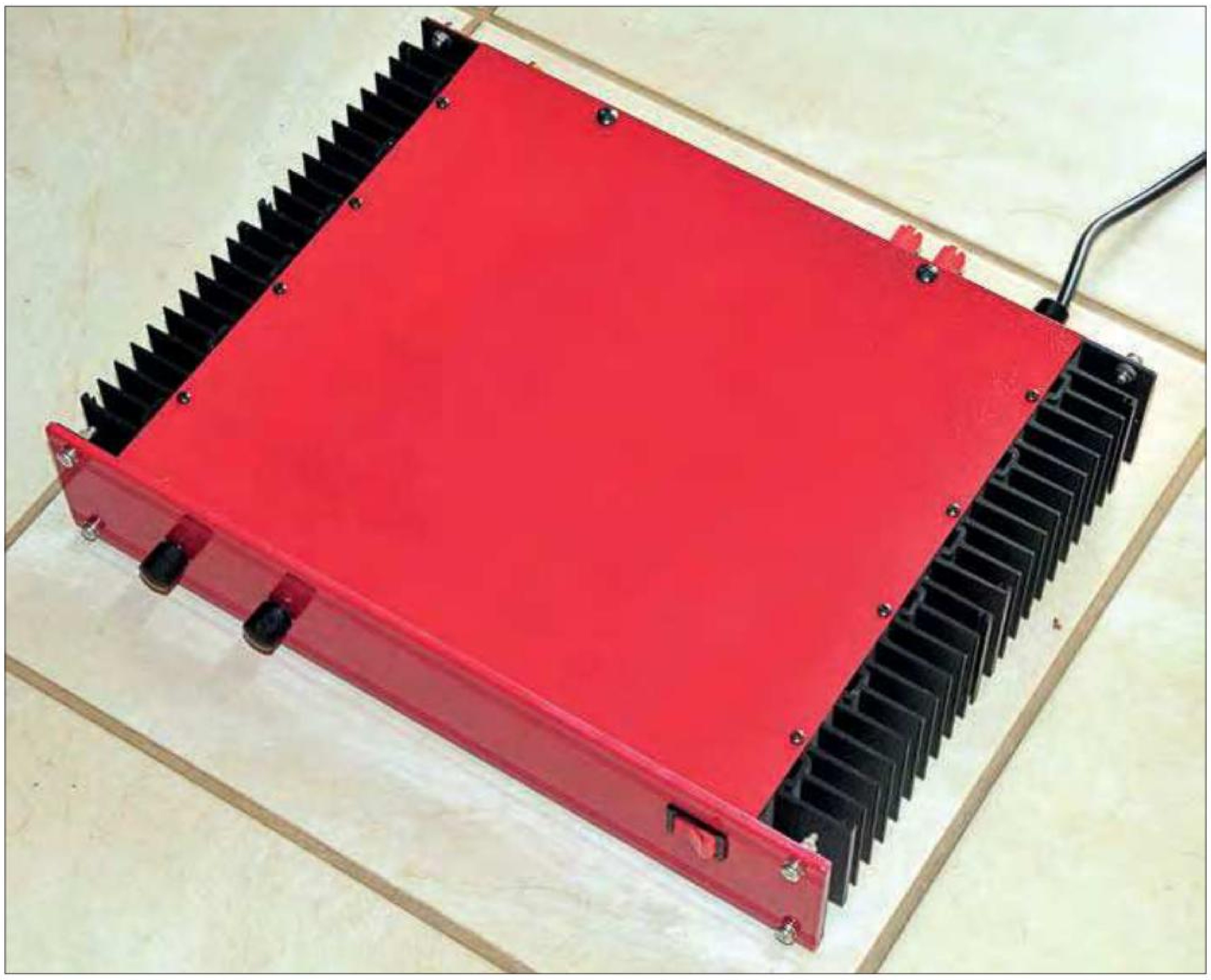


Fig.1. The completed 400W, two-channel amplifier. By using parts salvaged from a defective amplifier, construction cost was brought way down. With its heavy-duty case, chassis and heatsinks, it weighs 12kg. All the external panels were freshly painted in trademark Edgar red (see last month's pedal power station!).

requirement depends on the efficiency of the amplifier circuit design, and the 'double' rule might also stretch your budget a long way! (In the amplifier design covered in a moment, I used one 300VA transformer per nominal 200W module.)

So, unless the transformer in your salvaged amplifier is really unusual in its output voltage, or too low in its power capability, you should be able to find an off-the-shelf prebuilt or kit amplifier module that suits it.

The other approach is to start with the amplifier modules you intend using. Unless you are lucky, that means in turn you will probably need to buy the power transformer – but you may be able to salvage the filter capacitors and rectifier from your cast-off amplifier. There are really lots of ways of going about it, but:

- Do ensure that the power transformer output matches the amplifier board requirements in both voltage output and power
- If using a new power transformer and salvaged filter capacitors, check that the capacitors are still within their voltage ratings, and the rectifier within its current and voltage ratings.

You will also need to fit everything in the old case. However, unlike much electronics equipment, many amplifiers are relatively roomy inside, so this is not usually a problem. If, for example, you're aiming to fit a four-channel amplifier into an enclosure that once had only two-channel internals, do some careful measuring before buying any bits.

Doing it

My starting point was an old commercial amplifier, a two-channel design in a rack-mount enclosure. What attracted me to it were the very substantial heatsinks, one each side of the case, that used vertical fins. Because the natural convective airflow past the heatsinks is vertical, having vertical fins is likely to provide much better cooling than the more common horizontal fins. The other element that attracted my interest was that the amplifier was really heavy – and invariably with amplifiers, heavy = better! That might sound a bit of a simplification, but a heavy amplifier usually has a large transformer as well as a strong enclosure and big heatsinks.

I'd bought the amplifier – it came from the local recycling shop for about £10 – not expecting to use it as a salvage

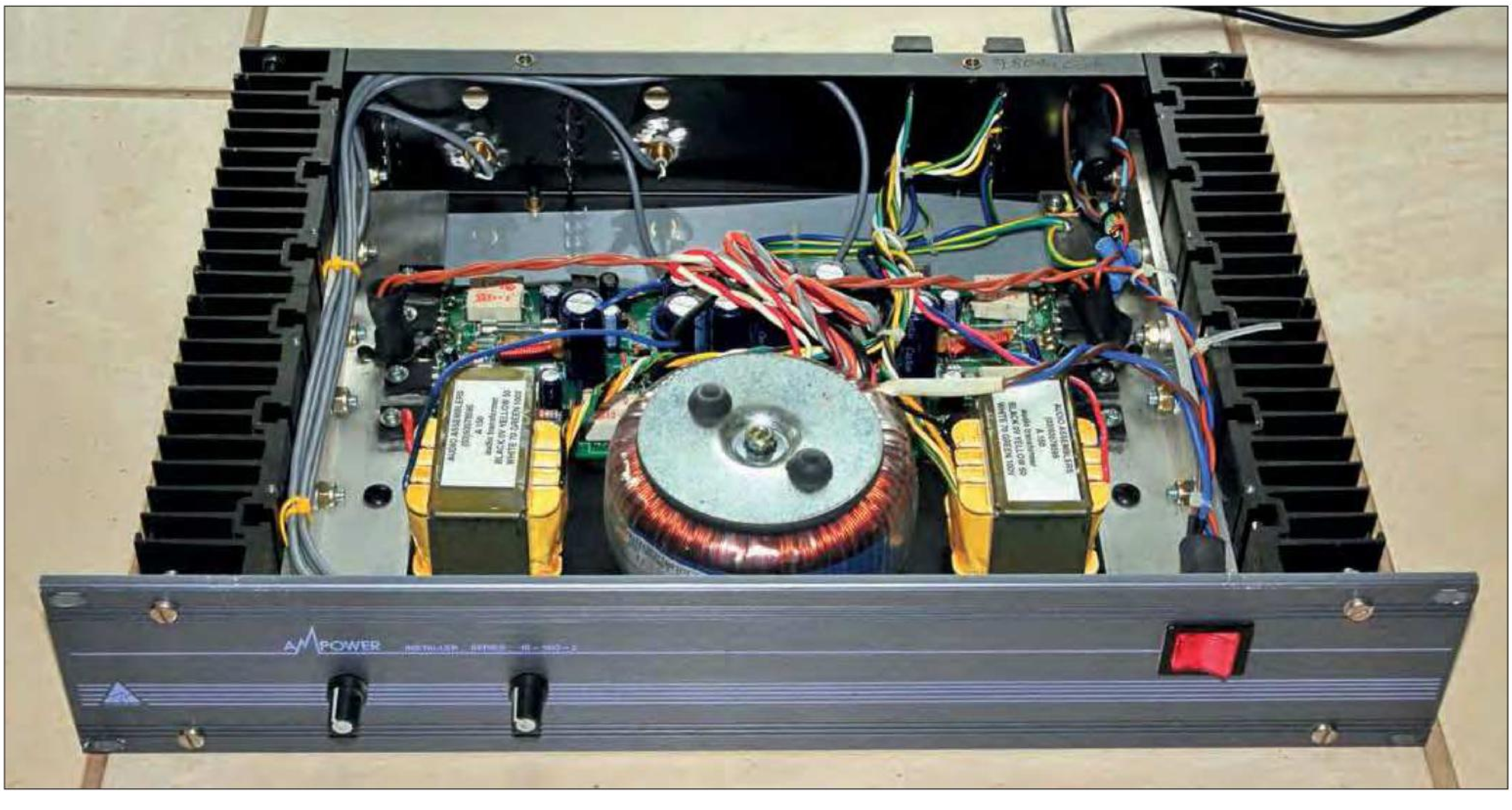


Fig.2. The salvaged commercial PA amplifier from which the enclosure, heatsinks and other parts were taken. This amplifier kept blowing an internal fuse – and without a circuit diagram, it wasn't worth chasing-down the fault.

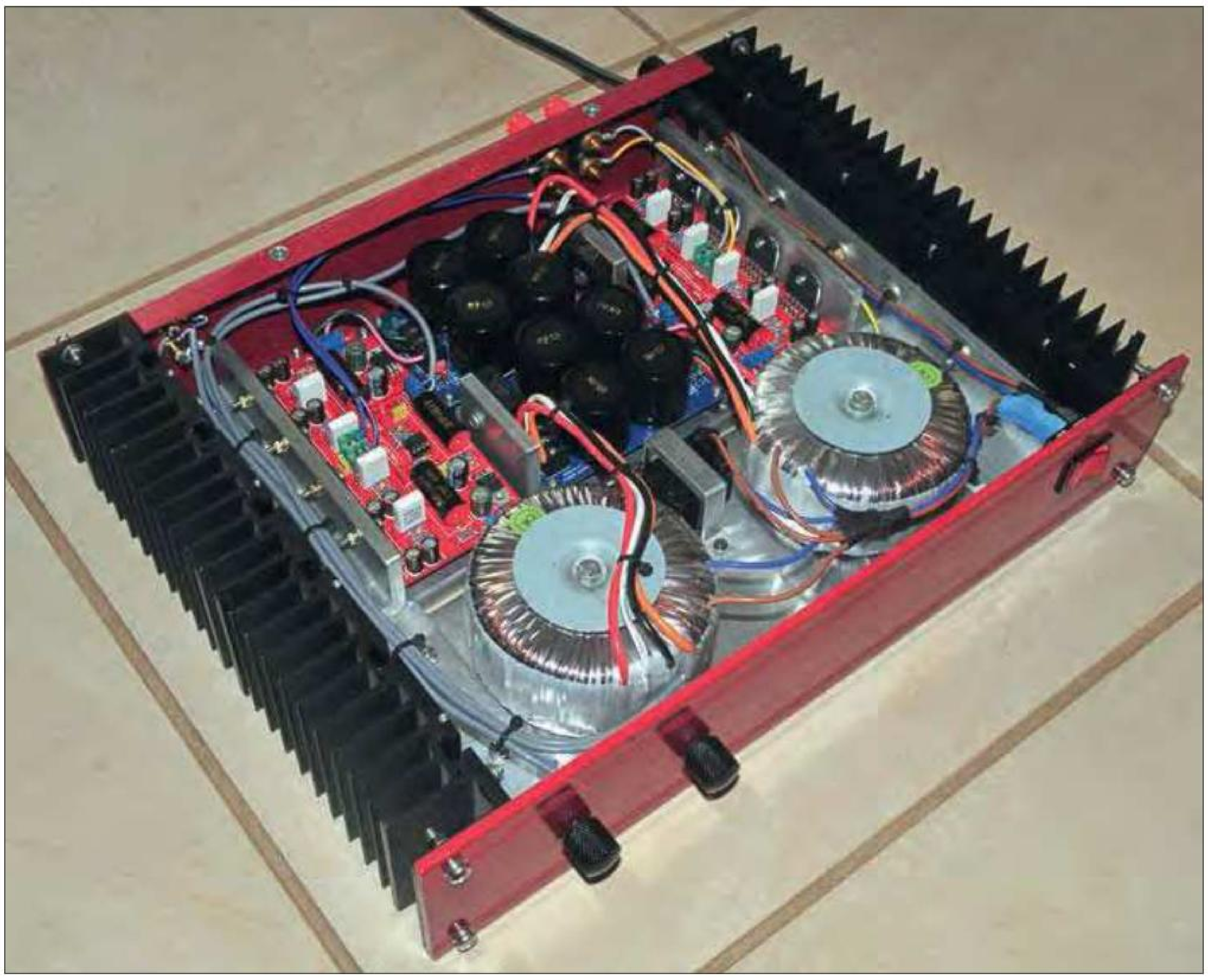


Fig.3. Inside the new amplifier. It uses two new transformers, their associated rectifier/capacitor modules, and new amplifier modules. The salvaged amplifier provided the case, heatsinks and bits and pieces like the mains switch, two volume controls and the input sockets.

amplifier; I thought in fact it might work! However, testing showed that it repeatedly blew an internal fuse when powered-up. It wasn't the main power fuse (implying that the transformer was still OK) but a fuse on the amplifier board itself. I could have tried fault-tracing, but to be honest, finding the problem in an amplifier I knew nothing about, and for which I didn't have a circuit diagram, was a bit much for me. So instead I decided to use it as the basis of a new amplifier.

The 300VA toroidal transformer had a measured output of 43-0-43V (that is, 43V measured across each winding, and 86V across both) which would have made it suitable for the aforesaid SC200 modules. However, in this case I'd already bought my amplifier modules, power supplies and transformers. These were:

- Two 200W mono LM3886 BTL amplifier boards
- 40,000µF capacitance, 35A rectifier power supply module
- 300VA, 25-0-25V toroidal transformer

Furthermore, in addition to the two LM3886 mono modules, I'd also bought two of the transformers and two of the power supplies. That is, I wanted to effectively build two completely separate mono amplifiers in the same case. Taking this dual-transformer approach can reduce costs over buying a single large transformer – especially if you already have one of the transformers.

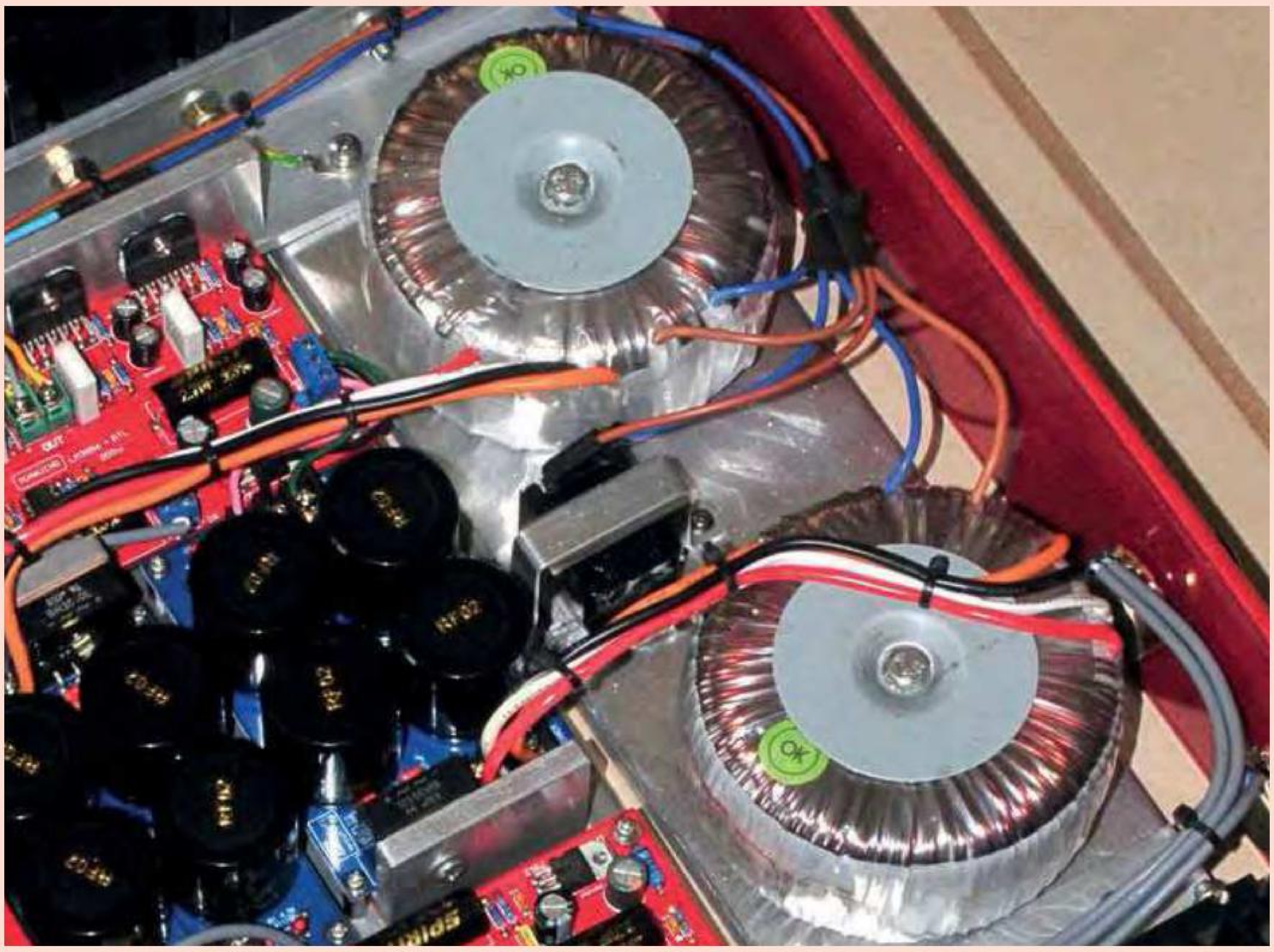
But would all the parts fit? The first step was to disassemble the salvaged amplifier. I removed the transformer and amplifier board (that incorporated the power supply) and studied what space I now had to work with.

Interestingly, the amplifier enclosure consisted of four large heatsinks, two joined along each side by heavy aluminium angle. In the original amplifier design, the output transistors bolted to this aluminium angle, that in turn conducted the heat to the main heatsinks. Bridging the gap between the heatsink sides of the amplifier was a folded aluminium sheet chassis on which the transformer sat. The main PCB just bridged the gap under its own strength. The front panel was a thick, machined aluminium sheet, while the back panel was a thin folded section, again made from aluminium.

Power supply for tone controls or speaker protection?

The amplifier, as shown here, doesn't use tone controls or external speaker protection. These extra boards typically require an AC 12V supply. Many amplifier transformers have an additional winding to provide this lower voltage. However, the transformers I was using didn't have these windings.

I therefore decided to provide an AC 12V power supply – just in case I later decided to add some more functions to the amp. The easiest way of providing this was to use the transformer from an old 9V DC plug-pack (wall wart). The plastic case of a plug-pack can be most easily opened by crushing it a little in a vice until it cracks open – there's normally plenty of room to squeeze the enclosure before the transformer inside is damaged. The small transformer was held in place by a metal strap.



The small transformer mounted between the toroidal power supply transformers is a 12V unit designed to power a speaker protection or tone control board, should one be added in the future.

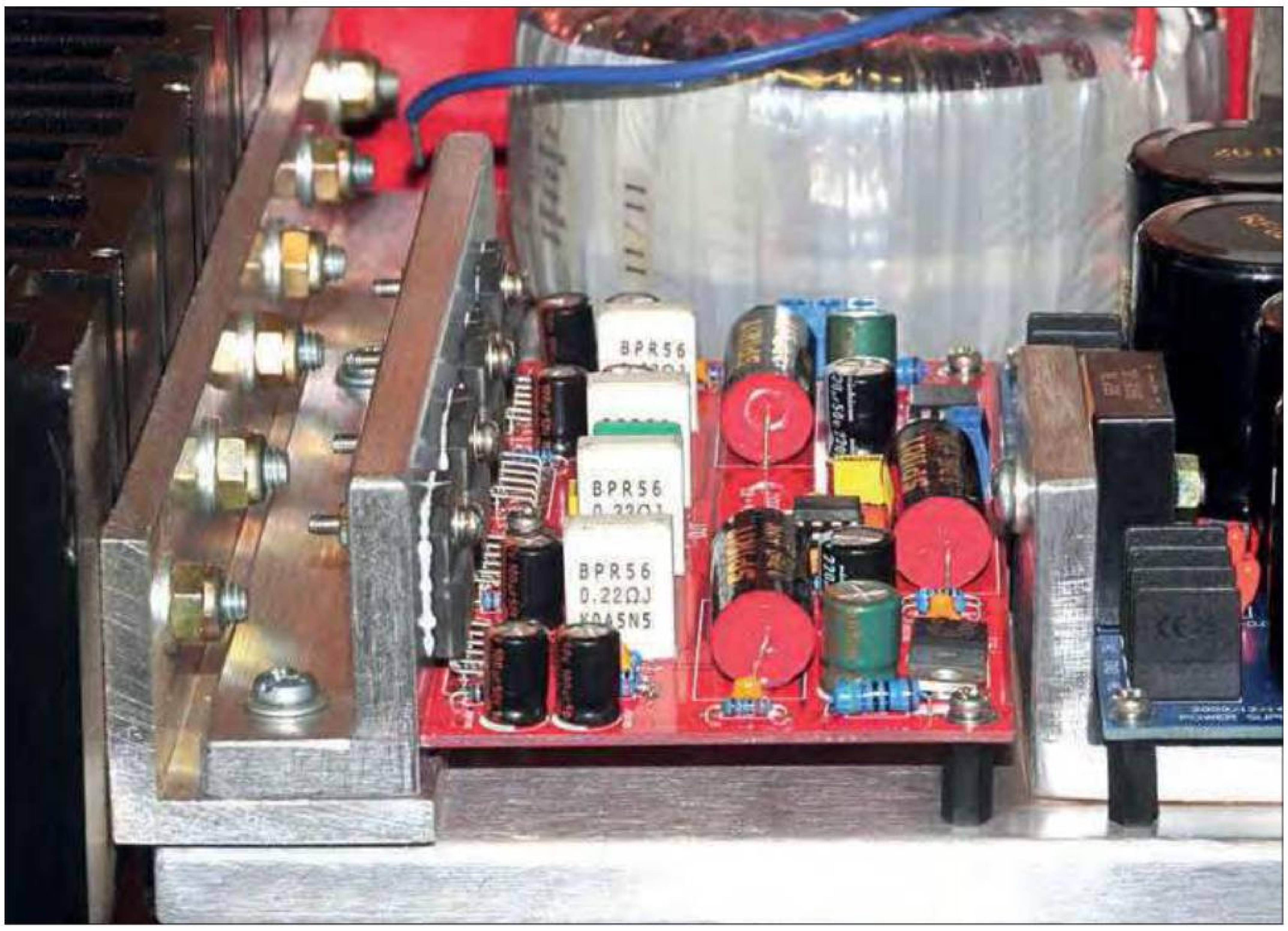


Fig.4. The view of the new amplifier with the rear panel removed. Note the heavy aluminium angle that connects the LM3886 modules to the original heatsinks, and the aluminium angle used to heatsink the bridge rectifier – it's thermally connected to the aluminium chassis below the boards.

Two steel cover sheets fitted top and bottom, attached to the heatsinks via screws.

The reasons for this detailed description are as follows. First, I could see that with some minor changes, almost the whole amplifier enclosure could act as a heatsink. To achieve that, all that was needed was to thermally bond the various aluminium parts together. Second, because the enclosure could be completely disassembled, the panels could be used as templates if I wanted to make any new ones. For example, and jumping ahead a little, the rear panel was full of holes for connectors I no longer needed. But by unscrewing the panel, it was fairly easy to make a replacement – the pattern was right in front of me!

Finding space

I moved my various newly bought components around in the space until I found an arrangement I thought could work. The output transistors of the new modules would need to be bolted to a new piece of aluminium angle that in turn could be bolted to the amplifier's original angle. This would add another step before the heat could get to the heatsinks, but I thought that if I used really heavy angle, it should still work fine. The two transformers could mount where the original transformer had sat – there was enough room on the original bridging chassis. However, because this panel had holes that were now in the wrong places, I made another from aluminium sheet.

But what of the power supplies – the fairy large boards containing the filter capacitors and rectifiers? The issue was heatsinking the rectifiers. I'd selected boards that mount the rectifiers at the edge of the PCB (many do not) so that I could attached heatsinks – but how was this to occur? There was no room to use the main heatsinks, and the very small heatsinks that could be attached would likely be insufficient. So instead I used a variation on the approach being taken with the main output transistors. I used heavy aluminium angle to attach the rectifiers to a new folded aluminium cross-chassis that supports the amplifier and power supply boards. This panel attaches to the heatsinks – so the rectifiers are effectively thermally connected to the main heatsinks – and the aluminium angle and bottom aluminium panel provide plenty of heatsinking, even if acting alone. (As I said, almost all the enclosure is a heatsink!)

So, let's take stock. Using the old panels as a template, I've made new rear and transformer support panels. I've also made a new panel that supports the amplifier and power supply boards, and additionally acts as a heatsink and thermal bridge for the rectifiers. From the original amplifier's enclosure, I am retaining the

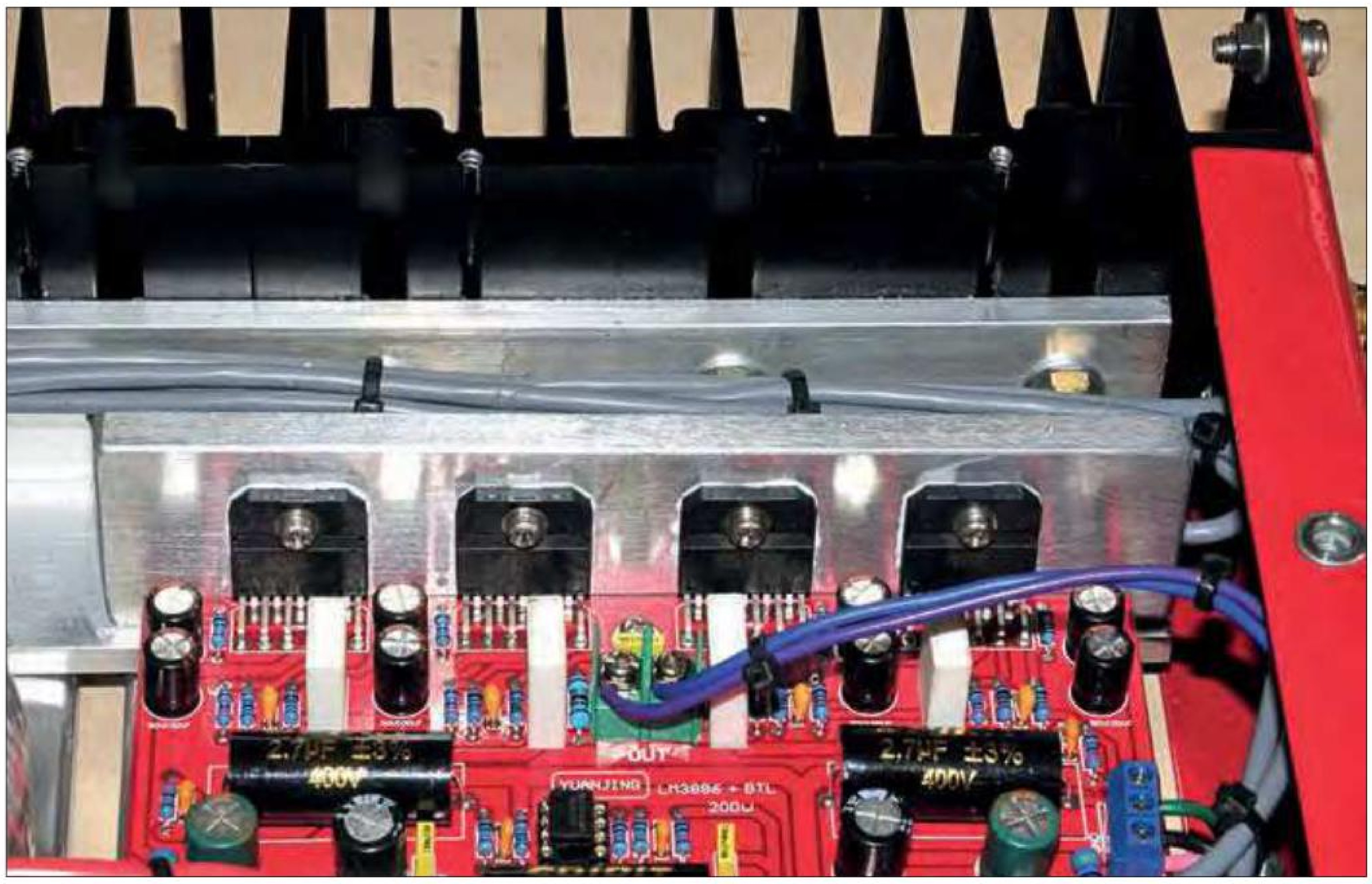
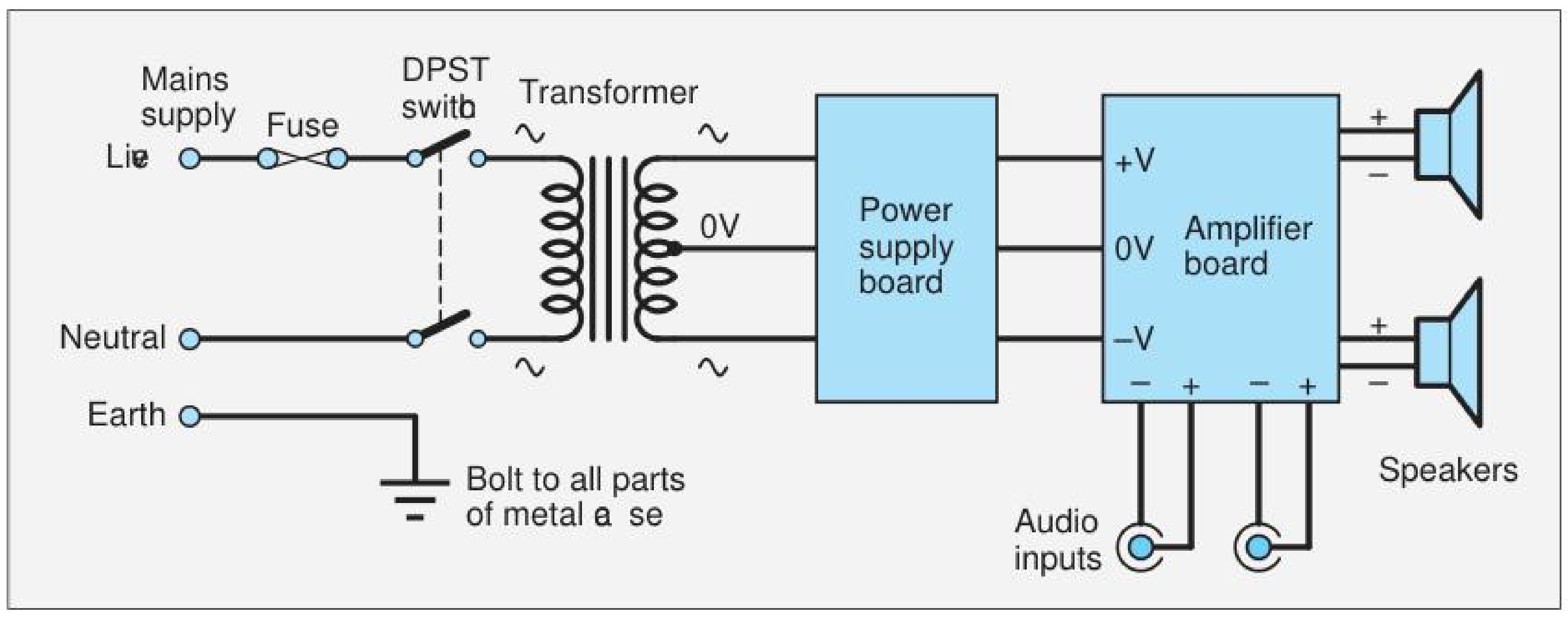


Fig.5. When applying heatsink compound, you should use sufficient that it just squeezes out all around the components, as here. In this amplifier, all the aluminium parts of the case are thermally connected using heatsink compound – the whole enclosure therefore acts as the heatsink.

Fig.6. If you are using prebuilt or kit modules for the power supply and amplifier boards, the circuit will look something like this. Variations include the powering of two amplifier boards (eg, two mono boards) from the one power supply, or the use of two transformers and two power supply modules, each powering one amplifier board. Important aspects to take note of are the use of the fuse and a double-pole, single-throw (DPST) switch on the mains input, the grounding of the mains earth lead to the metal case, and the observing of polarity with all the amplifier board connections.



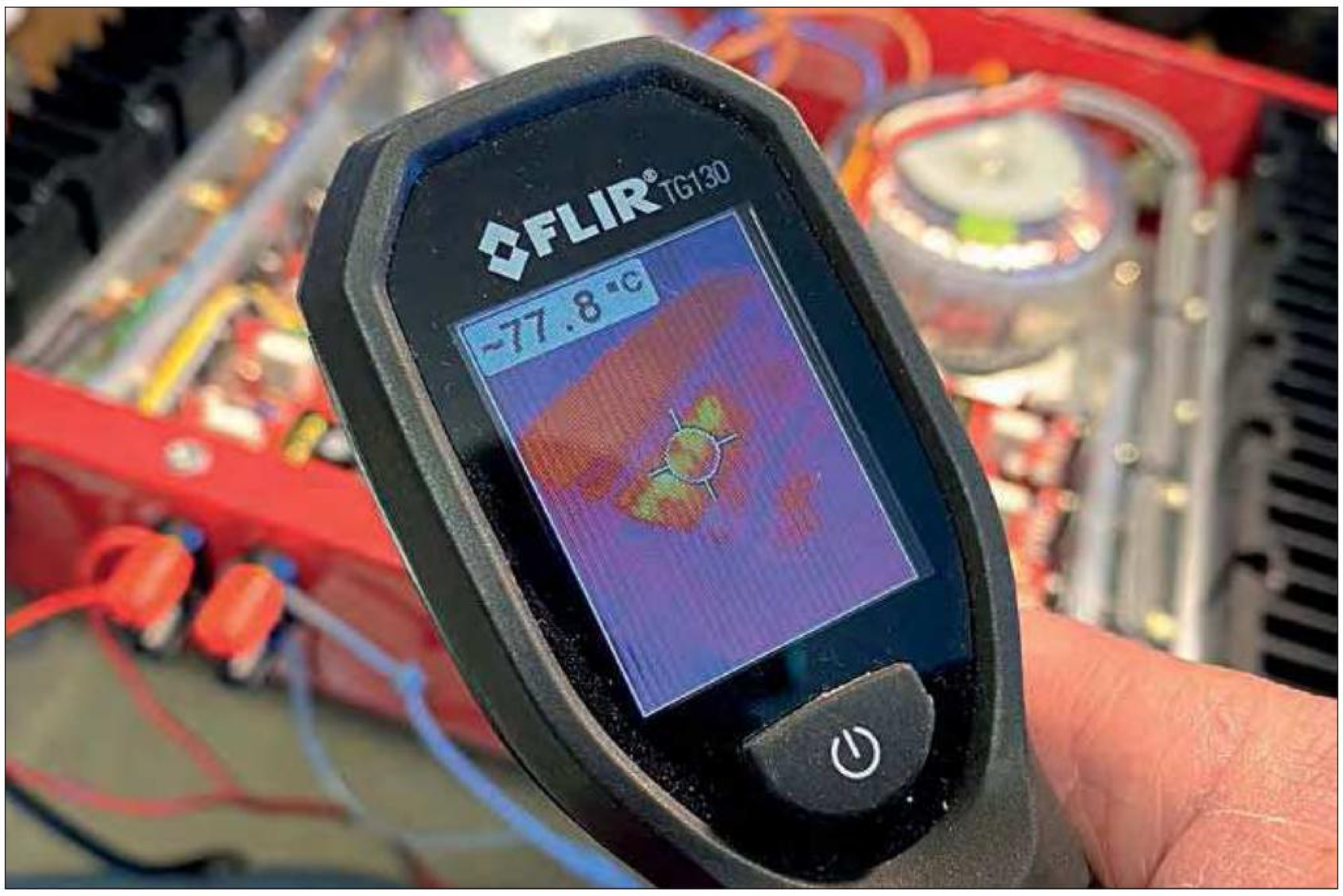


Fig.7. An infrared thermal image of the amplifier after about an hour playing music at full volume in 20°C ambient conditions. (It was so loud I needed to wear ear protectors.) The LM3886 ICs are running at just under 78°C. Their specified maximum junction temperature before auto-shutdown is 165°C.

large heatsinks and their joining aluminium angles, the front panel and the top and bottom cover panels. It may sound a bit like 'Grandpa's axe', but in fact it was much easier (and cheaper) taking this approach than starting with a new general-purpose (eg, rack-mount) enclosure and new heatsinks. The main benefit was that the big original heatsinks actually form the sides of the original amplifier enclosure, allowing direct access.

Wiring

The wiring is fairly straightforward, but as with any electronic project, you should test what you are doing, step-by-step. A typical overview is shown in Fig.6 which, for simplicity, shows a generic wiring diagram for an audio amplifier using a single transformer and power supply board, and a two-channel amplifier board.

The first thing I did was arrange the mains power wiring. Note the use in Fig.6 of the double-pole, single-throw (DPST) mains-rated switch. I used the one from the salvaged amp – a hefty unit with an inbuilt neon, rated at 20A. (That should last, even with the turn-on gulp of the capacitors.) The live (hot) lead should have a fuse holder inserted in it, immediately the cable enters the case. I used a 10A fuse – a 5A fuse is typically recommended for each 300VA transformer. Don't forget to securely anchor the mains cable (eg, with a clamp) so it cannot come loose. Cover all the exposed mains power connections with heat-shrink.

On the other side of the switch are the connections to the transformer. Multiple transformers are wired in the same way – ie, in parallel.

The earth (ground) connection should be made from the mains cable to a metallic part of the chassis eg, by an eye terminal and screw and nut. Use the continuity function on a multimeter to ensure that all metal parts of the amplifier are also connected to the ground terminal. If you find some panels are not connected, you must add some additional earthing wires.

Once you have the mains power connected and made safe, switch on and measure the outputs of the transformer (or in my case, transformers). The measured voltages should be near to the transformer specs (or, where you are using the transformer from the salvaged amplifier, as was previously measured).

Switch off power and now make the connections to the rectifier/capacitor module(s). This should be as simple as the wiring diagram shows – these boards are always well-labelled. Once you have done this, switch on and ensure you have the required plus/minus DC voltages on the outputs. Then, switch off power again and make the power connections to the amplifier modules, being careful to observe the correct polarities.

The connections to the speaker terminals can next be made. Again, be careful to observe polarity. Finally, wire-in the audio inputs. You can either use chassis-mount sockets (as I did, using the RCA sockets salvaged from the old amplifier) or use flying leads eg, cut-down 'extension' type RCA leads that have a female socket at one end. To reduce noise, use screened (shielded) cable for the inputs, connecting the screen to the negative terminals. Try to keep the input leads as far away from the transformer, power supply and speaker leads as possible.

Outcome

Over the years I have built many amplifiers – and listened to a great deal more. Perhaps I am a philistine, but with mega-dollar amplifiers I usually find it pretty hard to hear what some others rave about. For me, if an amplifier has flat frequency response, low background noise at high volume and no audible distortion at low or high listening levels, it's a good amp. And this one has all those characteristics – I am very happy with it.

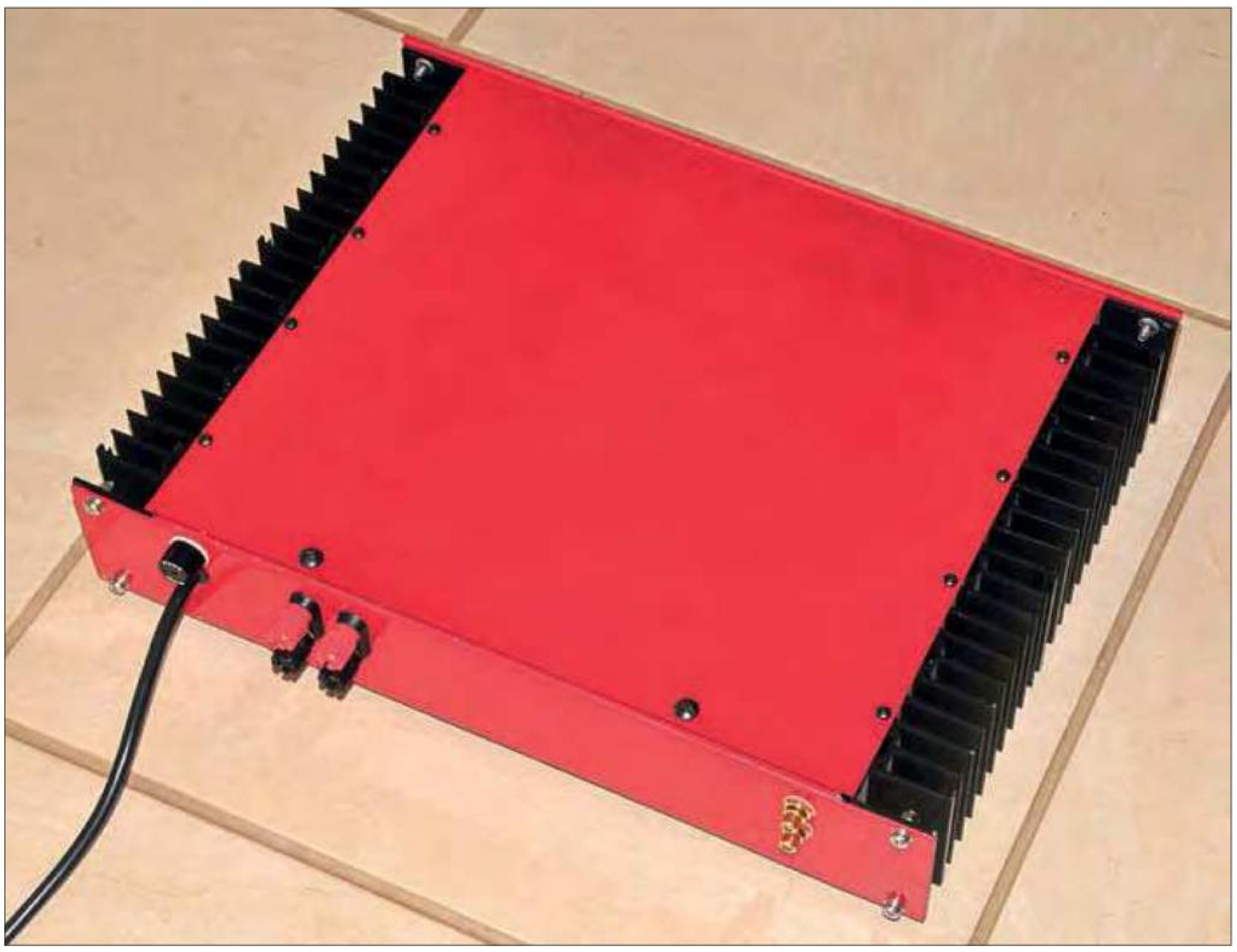


Fig.8. The rear view. From left, mains cable and fuse, speaker terminals and RCA inputs. As the donor amplifier's rear panel had many unwanted holes, a new rear panel was folded from aluminium sheet. Ensure you use rubber feet under the amplifier so that the heatsinks are raised off the ground, allowing better airflow circulation.

AUDIO OUT

By Jake Rothman

Theremin Audio Amplifier – Part 2

Last month, we introduced our dedicated *PE Theremin* amplifier – this month we will build it.

Construction

The PCB overlay is shown in Fig.10. It's an ideal beginner's PCB, no surface-mount technology, just well-spaced traditional ('jellybean', as our American friends call them) components. All the transistors are TO92 centre-base devices. The numbering is next to the component, not underneath, for ease of checking. Note the transistors annotation is 'Q' rather than 'TR'. This is the default in Eagle CAD.

As usual, solder the resistors in first, in the same direction for easy reading. Next, solder the transistors and pre-sets. Do the middle wire first, then bend them so they are straight, then solder the other two. Finally, insert the tall electrolytics. There's provision for bigger power transistors with centre-pin collector packages for more advanced constructors. These are on the periphery of the board to allow for heat sinking. Note the bias transistor, TR3 is designed to be thermally coupled to one of the output transistors TR4. Fig.11 shows the completed PCB.

Parts list

(Low-power version only)

Resistors

All resitors are 0.25W 5% carbon-film or 1% metal-film for lower noise

R1	12kΩ
R2	100kΩ
R3	270kΩ
R4	150Ω
R5, R6	3.3kΩ
R7, R8	1kΩ
R9	620Ω
R10	68Ω
R11, R12	1Ω
R13	22Ω
R14	10kΩ
VR1	1kΩ TO5 outline pre-set Rapid 68-0044 Truohm
VR2	5kΩ TO5 outline pre-set Rapid 68-0288 Suntan

Alternatively, cheap 5/6mm semi-open presets, such as Rapid Suntan 68-1574 can be fitted in the other holes.

Capacitors

C1	470nF any type. If using a polarised type make sure plus end goes to R1 pointing into board.
C2	22µF 3V (minimum) radial electrolytic or tantalum bead
C3	6.8µF 10V radial electrolytic or tantalum bead
C4	100µF 10V radial electrolytic
C5	22µF 10V radial electrolytic or tantalum bead
C6	22nF polyester 5mm
C7	220µF 10V radial electrolytic
C8	470µF 10V radial electrolytic
C9	15pF ceramic
C10	8.2pF ceramic
C11	10µF 6.3V(minimum) radial electrolytic

Semiconductors

TR1	BC549C small-signal high H_{fe} NPN
TR2, 3	BC549C small-signal high H_{fe} NPN
TR4	BC337-40 medium-power NPN
TR5	BC327-40 medium-power PNP
D1	BAT86 or other small signal Schottky diode
LED 1	standard 3mm red diode

Miscellaneous

PCB from *PE PCB Service* (AO-1220-01)

Loudspeaker: 25Ω 90mm EuroTec (available from author: jrothman1962@gmail.com)

Testing

Always use some form of current limiting when testing power amplifiers. A PP3 battery normally has a high enough internal resistance to provide this. Exceptions are rechargeable batteries and lithium smoke-alarm batteries, I saw a student burn his tongue doing the 'lick-test' on one! However, if a bench PSU is used, set it to below 300mA because this is the maximum collector current (I_C) of most small transistors. The DC bias preset PR1 should be set midway. Make sure the quiescent current preset PR2 is set fully anticlockwise for minimum current before turning on. This is tweaked to remove crossover distortion caused by the dead-band where one output transistor

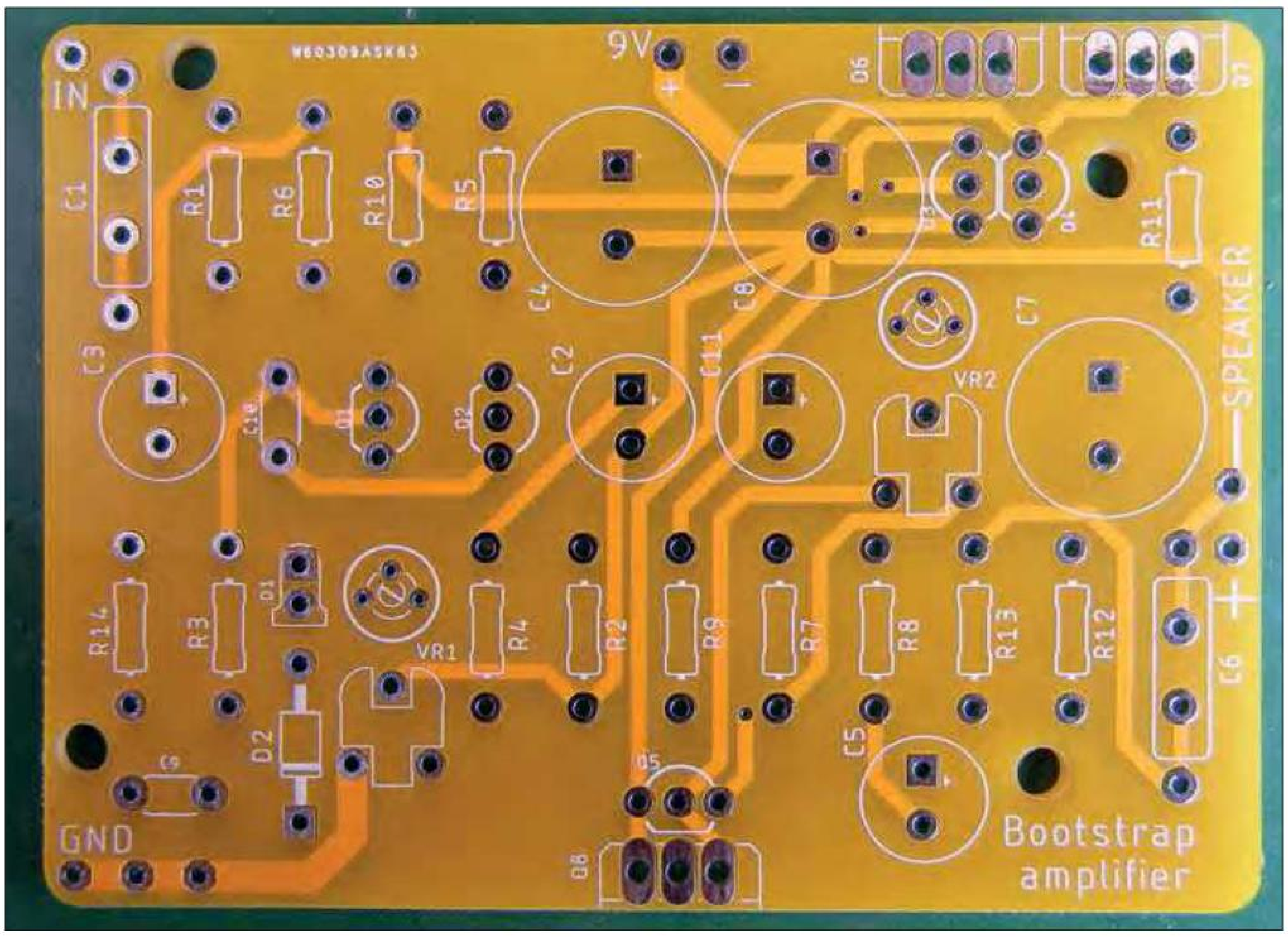


Fig.10. PCB overlay – note the power supply noding on the main decoupling capacitor, C8.

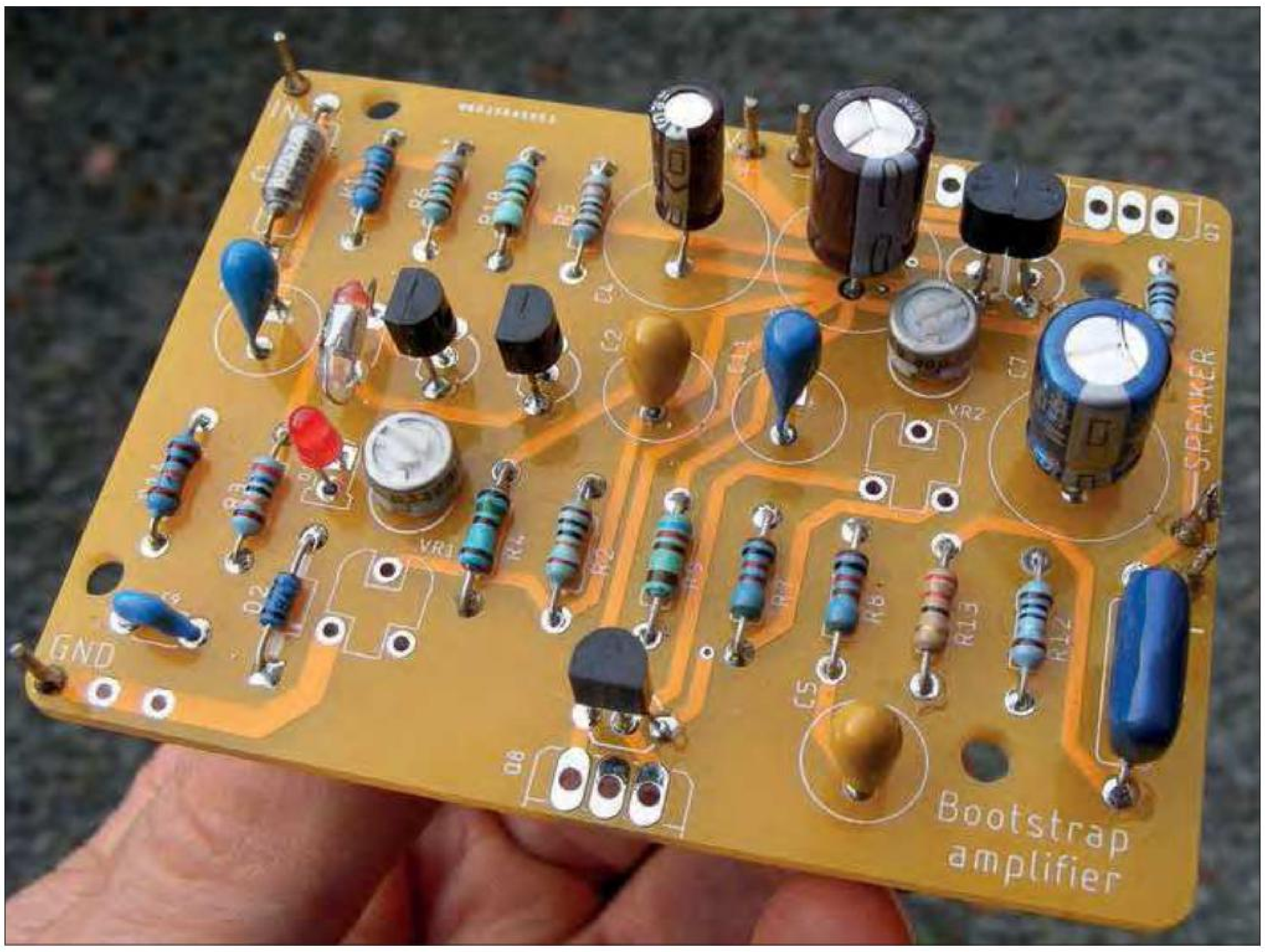

IN
GND
SPEAKER
VR1
VR2
Bootstrap amplifier

Fig.11. Completed PCB. Note how TR3 and TR4 are pressed together for thermal coupling, to keep the quiescent current stable.

turns off just before the other output transistor turns on during the output cycle.

These adjustments can be done by ear with a signal generator, but it's more accurate with a scope. It's a good idea to listen as you look at the screen. It's an essential part of one's audio education to correlate what one sees with what one hears.

Quiescent current

A 300Hz sinewave test set to give an output of around 2.5V$_{pk\text{-}pk}$ (peak to peak) across the load is particularly revealing of crossover distortion when setting up by ear. The preset is turned clockwise until the distortion just disappears and no more. The current consumption must be monitored with no signal. If it's turned up too much, thermal runaway may occur and cook the output transistors. Crossover harmonics are odd high-order, such as seventh and ninth, and a higher frequency test signal such as 1kHz will mask them. It's interesting that the high low-order, second and third, distortions of loudspeakers do not mask the edgy crossover distortion generated by class-B amplifiers.

Mid-point bias

Mid-point bias is not necessarily exactly half the supply voltage because of battery voltage droop, circuit asymmetries and speaker impedance. This is best done with a scope at 1kHz to get equal clip, top and bottom of the sinewave. If it clips one side before the other, maximum power before gross distortion sets in is reduced. Of course, this can be done by ear, just tune for maximum output without distortion.

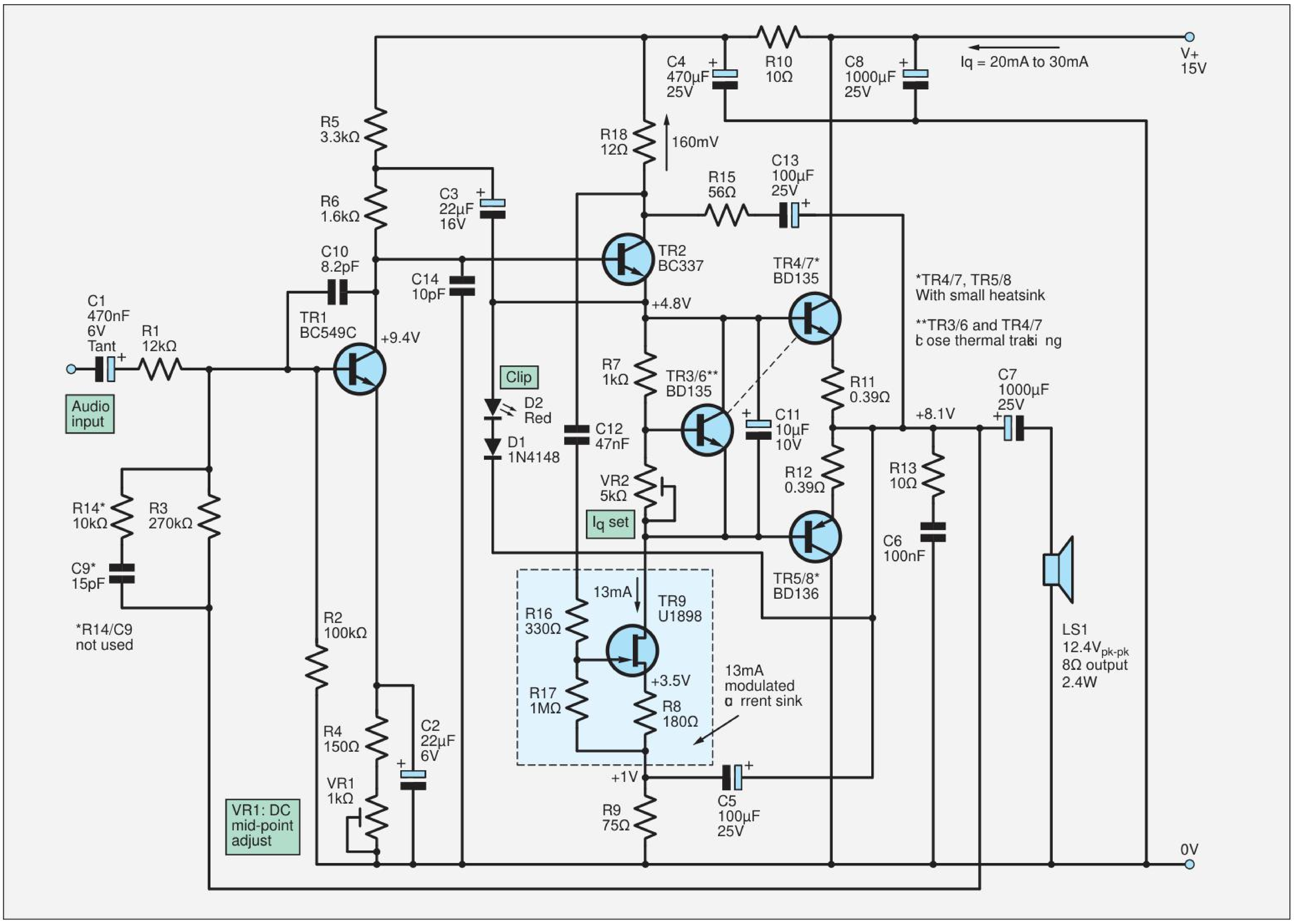

C4 470µF 25V
R10 10Ω
C8 1000µF 25V
Iq = 20mA to 30mA
V+ 15V
R5 3.3kΩ
R18 12Ω
160mV
C13 100µF 25V
R15 56Ω
R6 1.6kΩ
C3 22µF 16V
TR2 BC337
TR4/7* BD135
C10 8.2pF
C14 10pF
+4.8V
*TR4/7, TR5/8 With small heatsink
**TR3/6 and TR4/7 close thermal tracking
C1 470nF 6V Tant
R1 12kΩ
TR1 BC549C
+9.4V
Clip
D2 Red
R7 1kΩ
TR3/6** BD135
R11 0.39Ω
C7 1000µF 25V
Audio input
D1 1N4148
C12 47nF
C11 10µF 10V
+8.1V
VR2 5kΩ
R12 0.39Ω
R13 10Ω
R14* 10kΩ
R3 270kΩ
Iq set
C6 100nF
C9* 15pF
TR5/8* BD136
13mA
TR9 U1898
R16 330Ω
*R14/C9 not used
R2 100kΩ
LS1 12.4V pk-pk 8Ω output 2.4W
+3.5V
R17 1MΩ
13mA modulated current sink
R8 180Ω
R4 150Ω
C2 22µF 6V
+1V
VR1 1kΩ
R9 75Ω
C5 100µF 25V
VR1: DC mid-point adjust
0V

Fig.12. The addition of a modulated JFET current sink and extra bootstrapping enable the amplifier to be scaled up to 2.4W into 8Ω. The supply voltage is 15V, and I_q total is 30mA. Note the extra 10pF high-frequency stability capacitor, C14. Also note that feedback components C9 and R14 have been removed.

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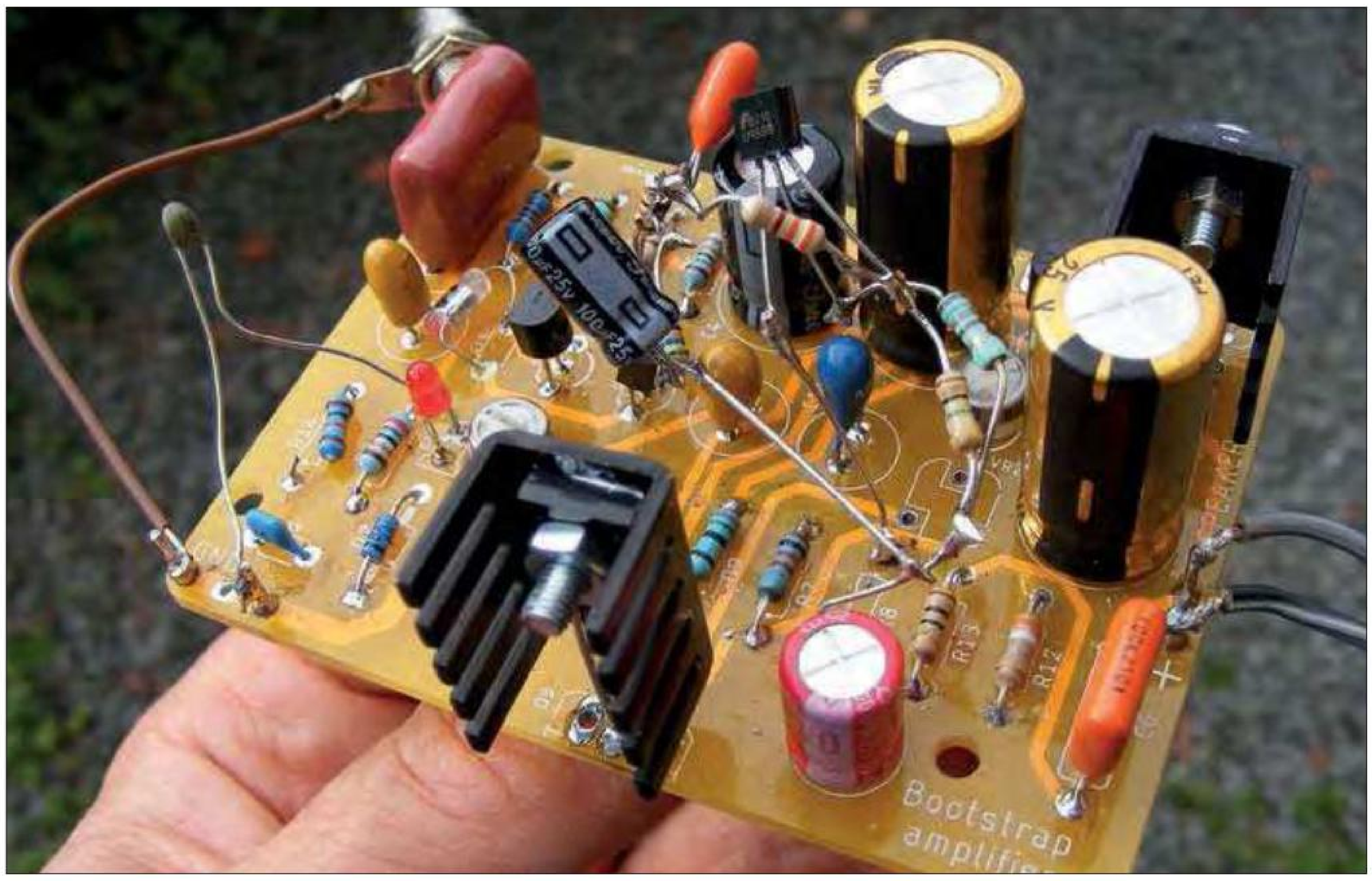

Fig.13. Modifications added to the PCB to give higher power and investigate bootstrapped current sink. Note the bigger output transistors with heatsinks. Oh dear, we need a new PCB design now –the price of tweaking!

Improvements and variations (experimenter's corner)

Resistor R8 can be replaced with a current source which allows the emitter-follower operating current to be reduced further. This is because the resistor itself is no longer soaking up useable audio power. Discrete fixed-value current sources, such as current-regulator diodes (CRDs), are another component that is becoming scarce and expensive. Rapid Electronics still have some left. I have new old stock. Don't even bother looking on other mainstream distributors for them, the 'generic pharmaceutical business model' means they now cost £1.50 each. Ten years ago

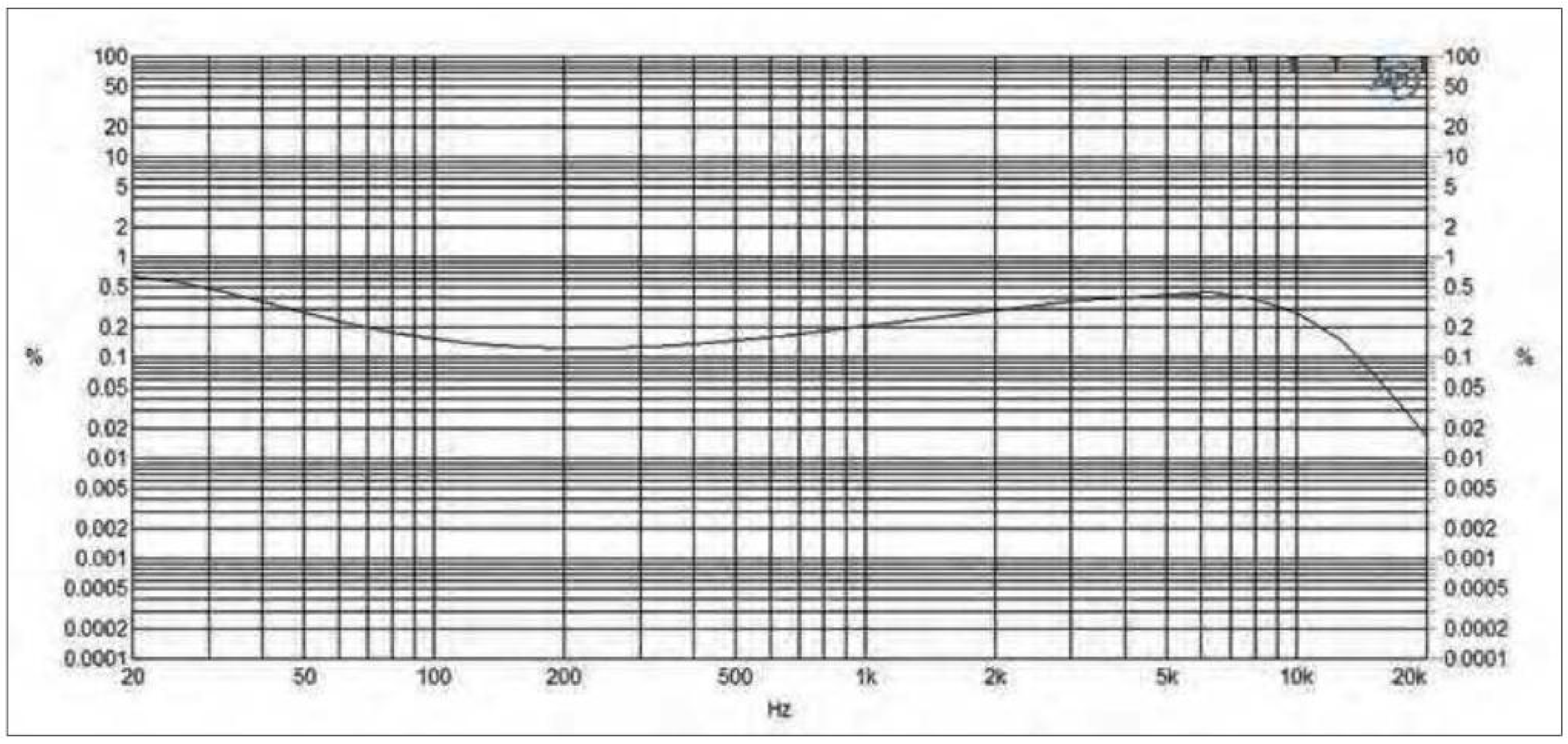

Fig.14. Distortion vs frequency curve of the *PE Theremin Amplifier* in Fig.9 at 6V pk-pk into 24Ω (190mW). Typical of small 1970s discrete amps.

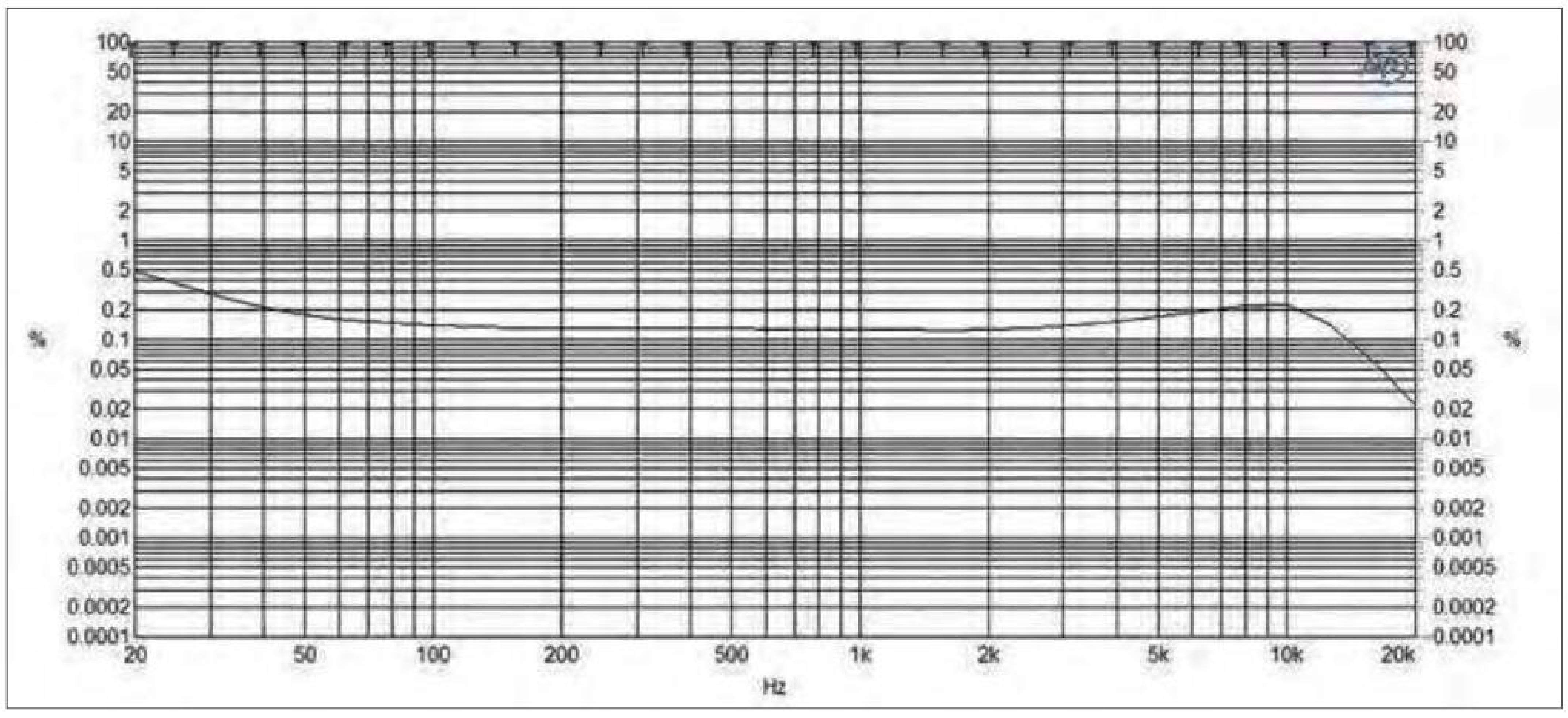

Fig.15. Distortion curve of the scaled-up circuit in Fig.12 at 7$V_{pk\text{-}pk}$ into 8Ω (760mW). 'Warm sounding' like the Mullard Hi-Fi amps in their applications book, *Transistor Audio and Radio Circuits* (1972).

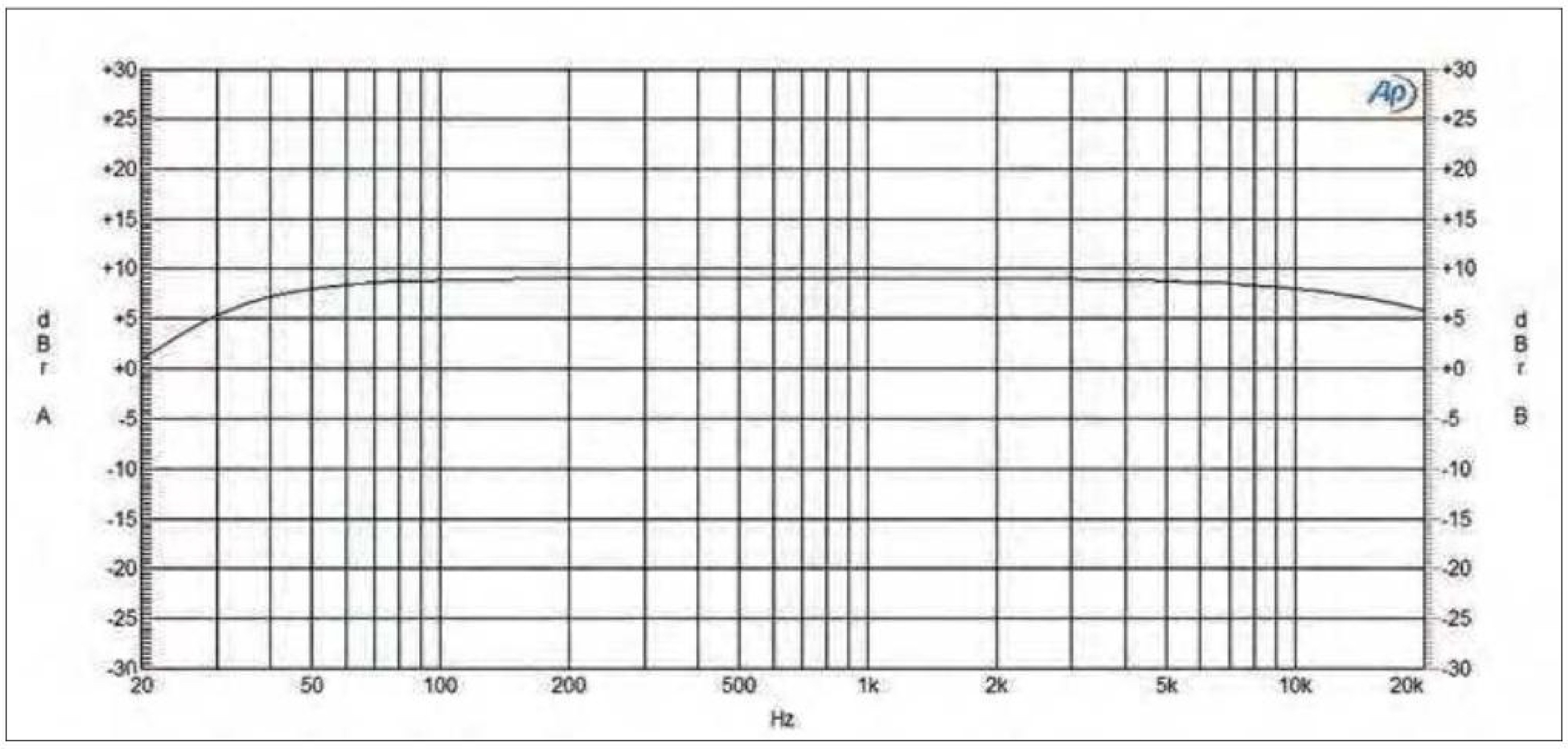

Fig.16, Frequency response of the *PE Theremin Amplifier*. The use of low-value capacitors gives a bit of bass loss. No problem given the small speaker used in Fig.1.

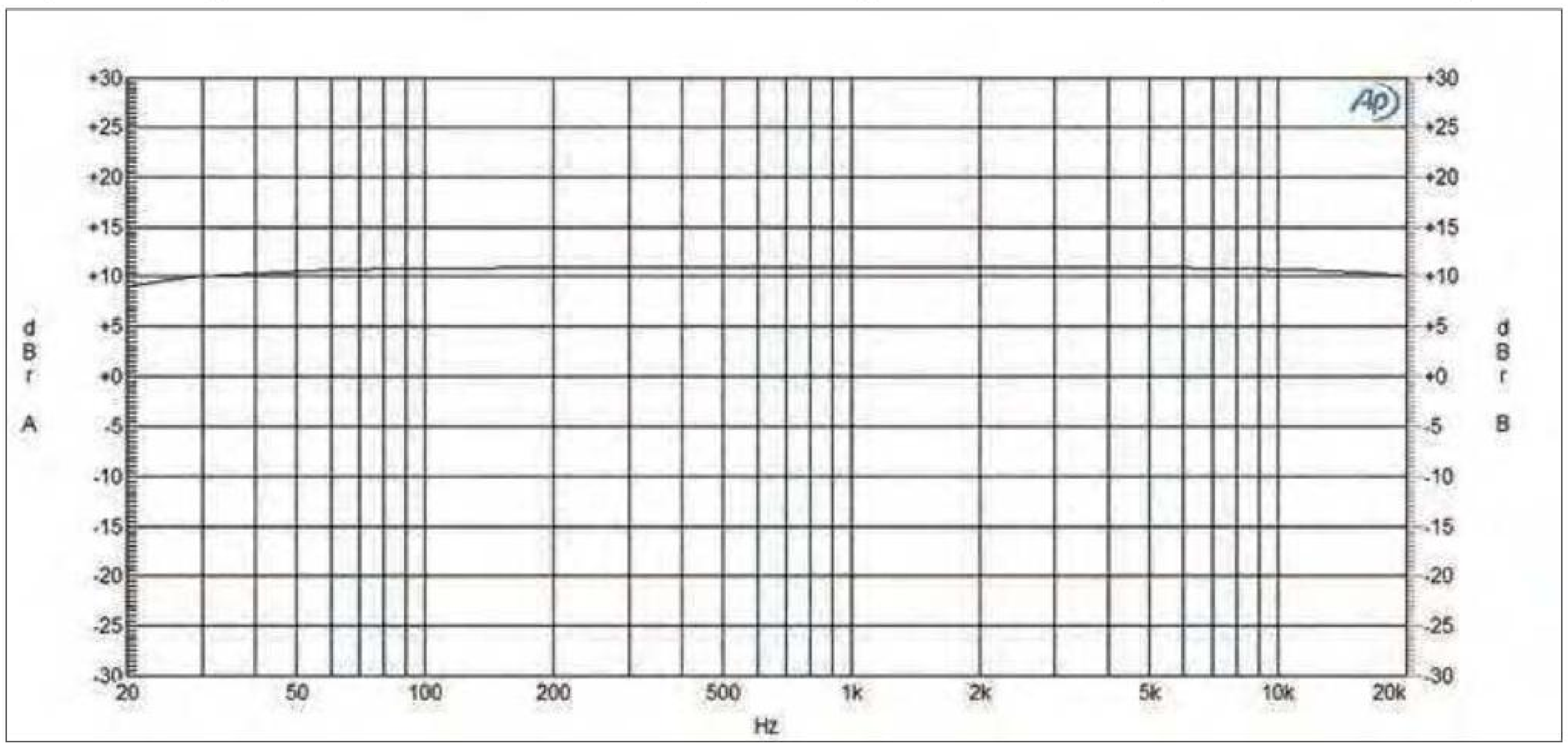

Fig.17. Frequency response of the higher-power version of the *PE Theremin Amplifier* in Fig.12. 1dB down at 20Hz and 20kHz – typical Hi-Fi response.

they were cheap. There are still variable current sources, such as the LM334, which are around 50p. Also, JFETs can be used, although wide tolerances on I_{dss} can give a two-to-one variation in current. Mouser still have lots of reasonably priced JFETs. These are a bit tricky to fit to the PCB since the devices have three leads and need a resistor or two.

Upping the power

The low output power may be insufficient for some people, so a circuit for experimenters using bigger output transistors and a JFET current sink is given in Fig.12. Resistor values are also reduced, increasing the currents to drive a lower speaker impedance of 8Ω. Of course, when the resistances are reduced, the capacitors have to be increased to avoid bass loss. The extra positions will accommodate TO220/TO126 outline transistors on the board. They have extra numbers TR7 and TR8 for the output, and TR6 for the V_{be} bias transistor which can be bolted to the heatsink for TR7. I used 40-year-old design ten-penny BD135/6 devices, but driver currents can be reduced by using some of the newer high current-gain lighting/converter bipolar transistors, such as the Zetex series and 2SA2039/2SC5706 types. Further improvements are a modulated JFET current source, shown in the circuit; this further minimises the current in the driver stage. Also, another bootstrap is employed on the top of the emitter-follower TR2 for greater voltage swing, using components R15 and C13. Of course, adding all these extra bits can be a bit messy, as shown in Fig.13! I hooked this amp up to an LS3/5A speaker and it sounded transparent and possibly 'warm' (a subjective audio word, meaning low-order harmonic distortion increasing in the low-frequency end).

Distortion measurements

I've recently bought an Audio Precision SYS2712 analyser from Stuart of Reading for £1500. Repair, calibration and the USB interface added another £1300. This sounds horrendous, but it's a tenth of its cost back in 2004. Some people hanker after Apple computers or Mercedes cars, but I've always wanted an AP. This is money well spent to obtaining quantitative measurements of the total harmonic distortion and noise (THD+N), allowing the effects of circuit changes to be seen instantly. This instrument will greatly enhance the circuits I lovingly design for the readers of *PE* and discriminate the 'audiofool' from audiophile components.

Fig.14. shows the relatively high distortion of the low-power amp. It is of no consequence with the *PE Theremin* and the small loudspeakers used, both of which have a THD+N of around 10%. Fig.15 shows the higher-power version, still technically 'bad' but not subjectively noticeable. Spectral analysis will probably show a lot of second harmonic present because of the asymmetry of the circuit. The frequency responses are shown in Fig.16 and Fig.17 respectively.

Germanium transistors

Since this is a minimum transistor design it was decided to investigate the use of some old (now expensive) germanium transistors. They are supposed to have increased voltage swing and softer distortion. I will reveal all next month!

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Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 23: Analogue inputs and servos

Throughout this series we have shown you how to interface different types of hardware (components and modules) to the Micromite. The Micromite is then programmed to act as 'an intelligent controller' to make the attached hardware behave as we want. The exact behaviour of the hardware is ultimately determined by software, or to be more specific, by the sequence of MMBASIC commands that are used within the program code.

Along the way we have demonstrated how to use buttons, infrared receivers, and GPS modules for inputs, and have used LEDs, motors and piezo sounders for outputs, as well as using various types of display modules. These have all used MMBASIC commands that are essentially based on *digital* signals; for example, standard on/off control of inputs and outputs (such as buttons and LEDs), or UART, SPI, or I^{2}C protocols to interact with devices (such as a GPS module, LED matrix or IPS display).

This month, we want to go right back to the basics and cover one area that has been requested by several *PE* readers; and that is to explore how to use the Micromite to read (and respond to) an *analogue* input. We will be demonstrating this by using a potentiometer to feed a variable voltage (between 0V and 3.3V) to an analogue input pin; and then use the relevant MMBASIC commands so that the voltage level can be measured. To make this a bit more interesting, we will use the input voltage (ie, the rotational position of the potentiometer) to control the position of a servomotor 'actuator arm' – see Fig.1.

Just two low-cost items are required to follow the topics this month: a linear potentiometer and a small servomotor (often just called a 'servo'). You may well have one, or both, of these items in your 'spare parts' drawer, but if not, they can be purchased online at minimal cost from many different sources – more on these items shortly.

Questions? Please email Phil at:
contactus@micromite.org

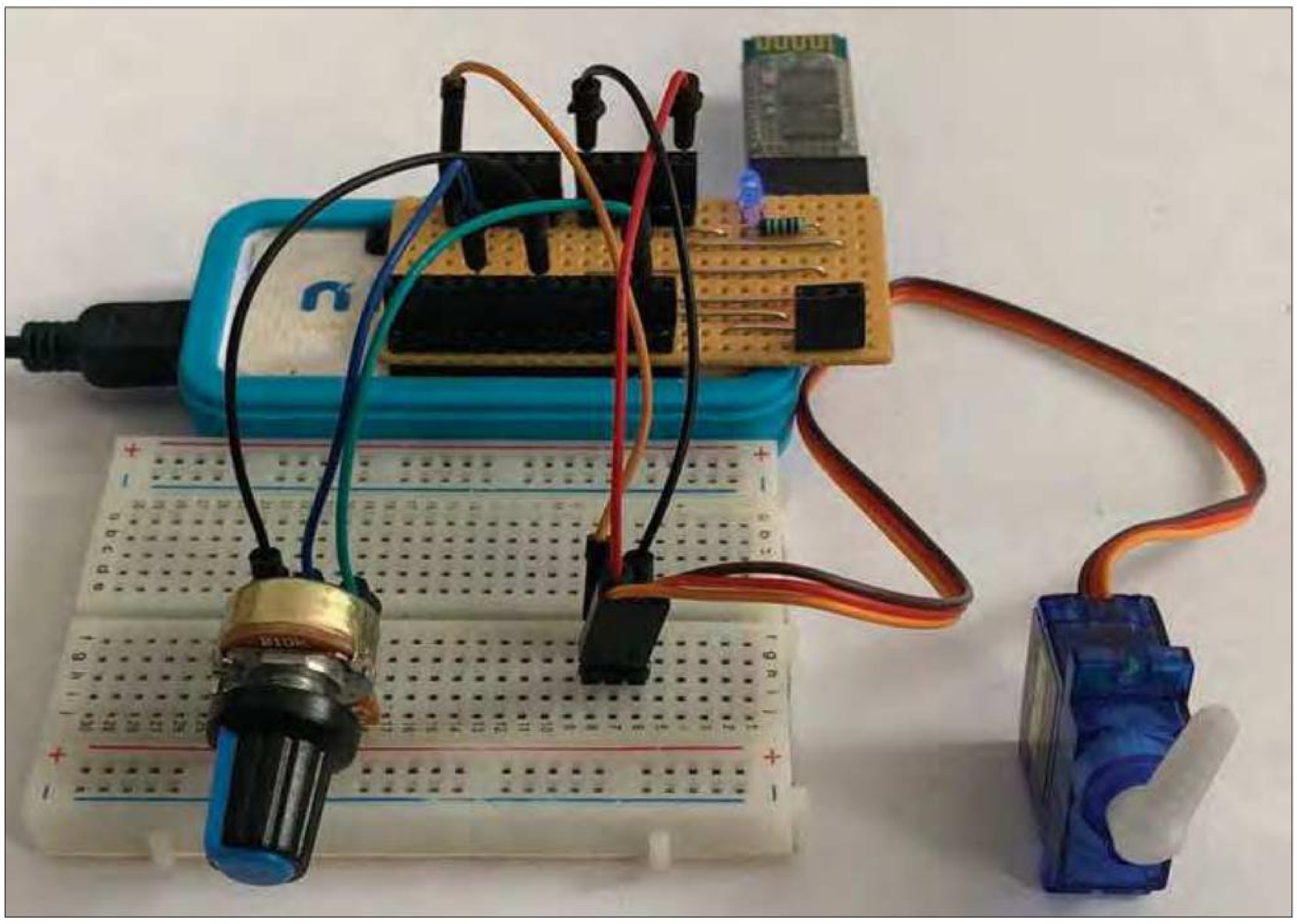

Fig.1. This month, we show how to read an analogue input (a voltage supplied by the potentiometer) and use it to control the actuator arm on a mini servomotor.

Available pins

Before we can start to connect anything to the Micromite we first need to understand which Micromite pins are available for use as an analogue input. Referring to Fig.2, you will see a representation of the I/O headers on our *Micromite Keyring Computer*. For now, ignore the servomotor at the top and the potentiometer at the bottom.

The position (and pin number) of the available analogue input pins are highlighted in grey. As you can see, there are ten analogue input pins available: pins 2-7, and pins 23-26.

Also highlighted in Fig.2 are the five PWM pins. The reason these are labelled is that each of these PWM pins can be used to control a servomotor instead of outputting a PWM signal. This is achieved in code by using the `SERVO` command instead of the `PWM` command – more on this later when we come to control our servomotor.

The 0V, 3.3V, and 5V header positions are also labelled. We'll need these when we connect the potentiometer and the servomotor (as you can see in the top and bottom of Fig.2).

Analogue voltage source

One of the first things learnt in electronics is Ohm's Law. We are not going to go into great detail here other than to say that we are using the concept of a potential divider (ie, two resistors connected in series) to effectively generate our variable voltage which we will then feed into our

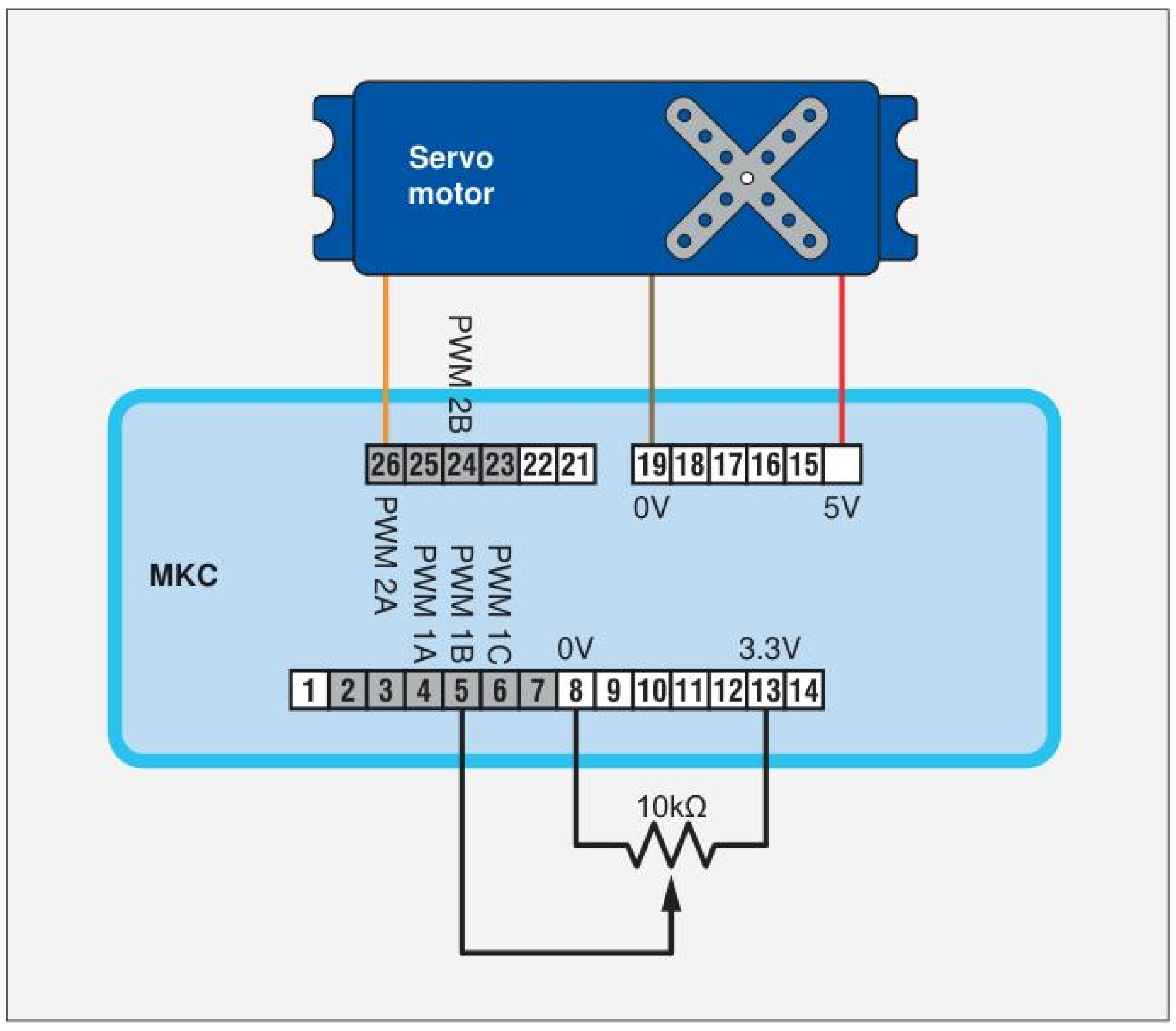

Fig.2. The position (and pin numbers) of the ten available analogue input pins are highlighted above, along with the five available PWM pins. Also shown are the connections to the potentiometer and servomotor.

analogue input pin. Fig.3a shows a simple example of a potential divider based on two 5kΩ resistors, connected in series, between 0V and 3.3V.

If we were to measure the voltage at Point A (relative to 0V), then without even using Ohm's Law we can see that it would be 3.3V. Likewise, Point C would be 0V. However, it is Point B that we are interested in, as this will be a voltage somewhere between 0V and 3.3V.

Since the two resistors are of equal value, then we can quickly conclude that the voltage at Point B would be half of the 3.3V applied across both resistors; ie, 1.65V. This can indeed be verified by calculation by using the familiar equation $V = IR$. For completeness, we will calculate it as follows:

Current through both resistors: $I = V/R$ = 3.3/(5,000 + 5,000) = 0.00033A (= 0.33mA)

Voltage across R2 = $I \times R$ = 0.00033 × 5,000 = 1.65V

The reason for showing this calculation is that if we were to vary the value of either R1 or R2, then the voltage at point B would change.

So, let us now consider a potentiometer, which is effectively a variable potential divider – refer to Fig.3b. Here, R1 + R2 = 10kΩ, and it is fixed by the actual value of the potentiometer. However, as the potentiometer's mechanical spindle (or slider) is adjusted, then the individual values of R1 and R2 will both vary, but they will always add up to a total of 10kΩ (or whatever is the value of the potentiometer).

Assume that our potentiometer has a spindle that is turned – much like a traditional volume control on an amplifier. At one end of spindle travel (eg, fully anti-clockwise), R1 will be 10kΩ, and R2 will be 0Ω, in which case Point B = 0V. At the other end of spindle travel (fully clockwise), then R1 = 0Ω, and R2 = 10kΩ, in which case Point B = 3.3V.

I did say that we would go back to basics, the reason being that I just wanted to demonstrate how a potentiometer can be used as the source of our variable analogue voltage. Fig.2 shows how to connect the potentiometer across the 3.3V supply, and the wiper (ie, point B in the explanation above) to analogue input Pin 5.

Go ahead and connect a potentiometer as shown by using whatever method works best for you. I prefer to plug the potentiometer directly into a breadboard, and then use jumper wires to the *MKC* (see Fig.1). However, you may prefer to solder wires onto your potentiometer. The only important point to mention is to ensure that you correctly identify the potentiometers wiper contact out of the three choices. This wiper-contact is the one connected to the Micromite's analogue input pin.

Note that it is safe to use a potentiometer with any value between 220Ω and 100kΩ; hence you will probably have something in your spares drawer that you can use straight away. If you have various potentiometer values to choose from then we suggest using one closest to 10kΩ as you can't do much damage with 0.33mA.

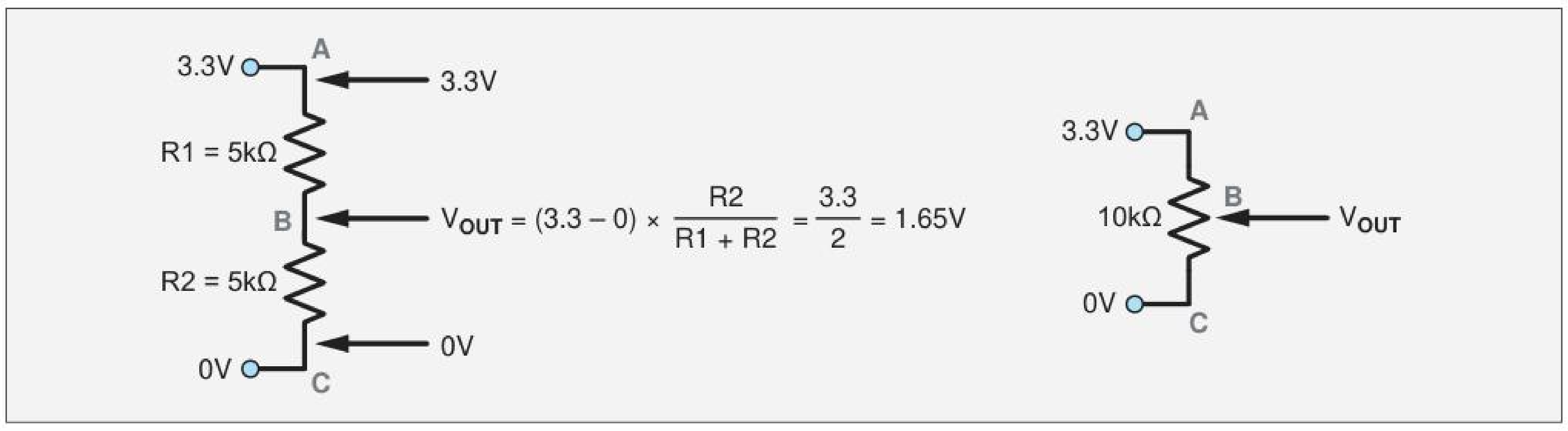

Fig.3 a) A potential divider comprisies two resistors; b) a potentiometer is effectively a variable potential divider.

MMBASIC `AIN` parameter

Now that we have an analogue voltage source connected to the *MKC*, let's proceed with how to measure it from within MMBASIC. Next, start your Terminal program so that you have a connection to your *MKC*, and get yourself to the command prompt (possibly press `Ctrl-C` should you have an auto-running program).

The first command we will require is `SETPIN`. We saw this early on in this series when we used it to configure an I/O pin to be either a digital input, or a digital output. As a reminder, we used:

- `SETPIN 3,DIN` for configuring pin 3 as a digital input (ie, detect button press)
- `SETPIN 4,DOUT` for configuring pin 4 as a digital output (ie, control an LED)

So to configure pin 5 as an analogue input, we simply follow the above format and use: `SETPIN 5,AIN`

Type this at the command prompt (then press the `Enter` key). You won't actually see anything happen apart from the cursor moving down to the next line – if you see an error message then simply correct anything mis-typed.

Now that we have configured Pin 5 as an analogue input, we can proceed with reading its value. This is really simple, as all you need to do is type: `PRINT PIN(5)` and press `Enter`. MMBASIC will then return the voltage value and display it on the terminal screen – try it now. Next, adjust your potentiometer, and repeat the `PRINT PIN(5)` command – you should now see a different value. There are two more things to check, and that is the measured voltages at each extremity of the potentiometer. So, turn it fully clockwise and check the voltage; and repeat for fully anti-clockwise. In one position you should see 0V, and in the other, 3.3V. Note that fully *anti-clockwise* may read 3.3V rather than 0V – this is not an error, it just depends on which way round you have the 0V and the 3.3V connected to the potentiometers end contacts.

One important point to note is that the *MKC's* analogue input pins can only read a voltage between 0V and 3.3V. Should you wish to read a higher analogue voltage then you will need to use external hardware (such as an op amp) to scale it down to between 0V and 3.3V.

Analogue voltage reader

We have just seen how to configure an analogue input pin, and also how to read the voltage level on the pin. However, this was all done directly from the command prompt. So let's now write a program that continually displays the voltage on the Terminal screen so that as we adjust the potentiometer we see the voltage value change on the screen. This is very easy to achieve, but we will need to use some VT100 Escape codes to help format the terminal display nicely. Now type the following seven-line program into your *MKC* (remember to save any work first, or alternatively, just insert these lines before the start of your existing code).

```
SETPIN 5,AIN
PRINT CHR$(27)+“[2J”
DO
  PRINT CHR$(27)+“[2;2H”;
  Vin=PIN(5)
  PRINT STR$(Vin,1,2);
LOOP
```

Before you run the program, let's first take a quick look at how it works (if you have been following this series then there won't be anything here you don't recognise).

The first line, as we have just seen, configures pin 5 as an analogue input. The second line uses an Escape code to clear the terminal screen. Then we have a `DO…LOOP` comprising three lines. The first of these lines positions the cursor 2 lines down the screen, and 2 characters along the line (ensure you type this exactly as shown above – case sensitive and with the semi-colon at the end of the line). This Escape code is used so that the cursor position is moved away from the top-left corner of the screen and hence makes it easier to read the voltage that we are about to display. The second line in the `DO…LOOP` loads a variable (that we have called `Vin`) with the measured analogue voltage on pin 5. We are storing the voltage value in a variable as we will not only be displaying the value on the screen, we will also be using it for a calculation when we add the servo (discussed shortly). The last line in the `DO…LOOP` displays the value on the screen and uses the `STR$()` command to format it to `1` leading digit along with `2` decimal places. The `STR$()` command is used because we need to convert a number (ie, `Vin`) into a string (something that can be displayed), so that we can then format it to the required number of characters (here `x.xx`). Doing this ensures that the displayed voltage appears to remain in a static position rather than jumping about.

Now `RUN` the program and check it works. As you adjust the potentiometer, you should see the displayed value vary. If not, check your wiring, and also that your code has been entered correctly. Do check that at one end of the potentiometer's travel the value is 0.00, and at the other end it is 3.30; however, do note that if you do not get exactly to 0.00 or 3.30 this will not be a fault of anything you have done; it will simply be down to the quality of the potentiometer.

A simple servo

Now that we have a method of adjusting an analogue voltage (between 0V and 3.3V), and also have the ability to read the voltage within our code, we can use it to control a mini servo. So what is a servo? Essentially, it is a motor with built-in positional control. It has a spindle that is typically limited to a rotational movement of 180° (half a turn). Onto the spindle you can attach an actuator arm, which in turn can be attached to something mechanical. For example, in a toy car, a servo's actuator arm may be attached to the front-wheel mechanism allowing the servo to steer the car.

A servo has three wires, two for power (5V in this case), and one for a control line. The control line requires a signal that is a square wave (within a certain frequency range). The square wave's duty cycle (the ratio of on-time to off-time) determines the position of the servo's spindle. MMBASIC makes it very easy to control a servo thanks to the `SERVO` command – this eliminates the need to worry about the signal timing, as we will see shortly.

If you don't have a servo in you spares drawer, then many are available online at a very low cost and we would recommend obtaining a few as they can be a lot fun to use. Please see Fig.4 for the type of mini servo we are using here.

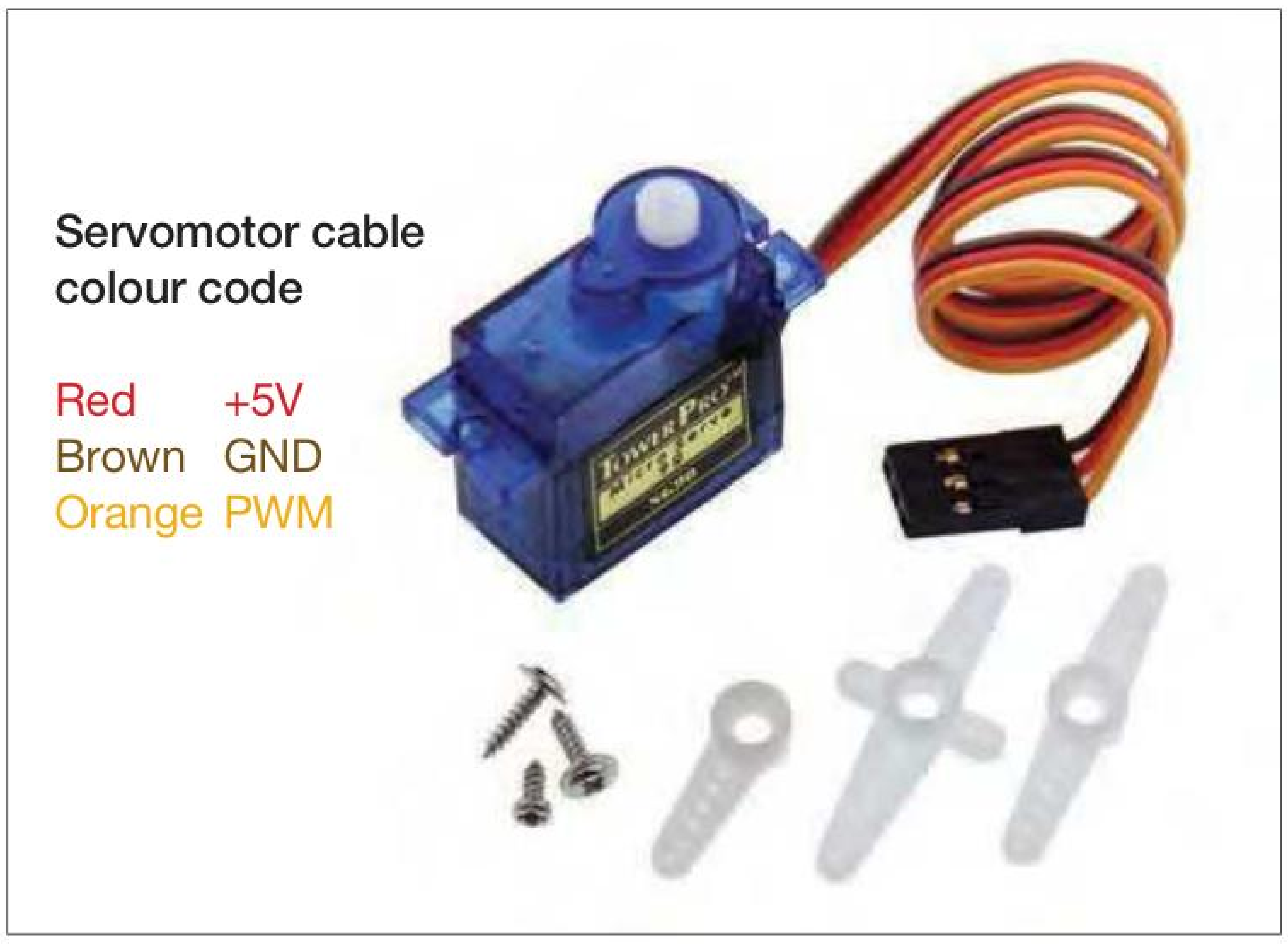

Fig.4: A low-cost mini servomotor is readily available online. It's a perfect match for MMBASIC's `SERVO` command.

MMBASIC `SERVO` command

You may recollect that we used the PWM pins earlier in the series (along with the `PWM` command) to drive a piezo buzzer. Essentially, the PWM command was used to adjust the frequency of a square wave that in turn was driving the piezo sounder; the end result enabled us to play different musical notes. For the purpose of music generation, the PWM command used a duty cycle of 50% – ie, a precise square wave. However, as mentioned above, a servo uses a specific frequency, and it is simply the duty-cycle that is adjusted in order to move the servo's spindle to a specified position. The duty-cycle value is represented as a time (in ms) with a typical value range from 0.8ms to 2.2ms for most servos.

MMBASIC's `SERVO` command has the following syntax:

```
SERVO channel, freq, duty-timeA[, duty-timeB,
duty-timeC]
```

Here, *`channel`* is set to `1` or `2` (depending on which Micromite pin is used – see pinout in Fig.1); *`freq`* is set to an appropriate value for the servo used (we will be using a frequency of 100Hz); and *`duty-time`* is the time (in milliseconds (ms)) as described above.

So, if you have a servo available, now is the time to connect it to your *MKC*. Simply connect the three leads as shown in Fig.2 – in other words, connect the servo's red lead to +5V, the servo's brown lead to 0V, and the orange lead to Pin 26. Do a quick check you have it connected correctly, and then start your Terminal app so that you have a connection to your *MKC* and can see the command prompt.

Next, type: `SERVO 2,100,1.2` and check that the servo moves. Note that it is better to add an actuator arm onto the servo's spindle so that you can clearly see it moving. If you don't have an actuator arm, just use a small piece of tape and attach it to the spindle to simulate a 'pointer'. If it does not move, then recheck your three connections, and also check that you have typed the command exactly as shown.

Now repeat the above but with a duty-time of 0.8 (instead of 1.2), and then try 2.2. You should then see the servo move near to its extreme positions covering an angle of close to 180°.

Potentiometer control of the servo

Now that we have connected up the servo, and seen how MMBASIC can be used to directly control the position of the servo, we will modify our program code from earlier so that turning the potentiometer adjusts the position of the servo's spindle. As always, this is much easier than it sounds; so go ahead and make the following changes by adding the four lines of code highlighted in bold:

```
MinVal=0.8
MaxVal=2.2
SETPIN 5,AIN
PRINT CHR$(27)+“[2J”
DO
  PRINT CHR$(27)+“[2;2H”;
  Vin=PIN(5)
  PRINT STR$(Vin,1,2);
  SerPos=((MaxVal–MinVal)*(Vin/3.3))+MinVal
  SERVO 2,100,SerPos
LOOP
```

Before running the program, we'll quickly explain what the four lines of code do that have just been added. The first two lines simply set two variables that we will use in a calculation within the `DO…LOOP`. If you look at the names and values, you should recognise that they represent the minimum and maximum values for the servo's duty time (in ms, as discussed earlier). Note that in the real world, different quality servos have different performances and specifications. It may be that your specific servo can work beyond these values, hence setting them in the first two lines of code makes it very easy to try different values that may well work with your servo. For now, though, leave them set to the values of `0.8` and `2.2`.

The third line added may look complex, but it is just a calculation that maps ('translates') a voltage value between 0 and 3.3 (from the potentiometer) to a value between `0.8` and `2.2` (ie, between `MinVal` and `MaxVal`) to be used by the `SERVO` command. The fourth line then uses the mapped/calculated value (which we have stored in the variable `SerPos`) and passes that to the servo.

Now `RUN` the program and make sure that the servo moves proportionally to the turning of the potentiometer. As usual, if anything does not work as expected, check your connections, and also check your code.

Challenges

There are many modifications that you could make to this month's code, and we would certainly encourage you to experiment. Here are two ideas to try:

- Change the `MinVal` and `MaxVal` values to find the optimum values that give you as near as 180° of spindle movement. Be careful doing this as the servo mechanism can be damaged if a relatively big (or little) value is used in error. I advise applying 0.1ms step changes at a time.
- Get the spindle to move in the opposite direction. This could be achieved by simply swapping the two 0V and 3.3V wires on the potentiometer (try it and see!). However, imagine the scenario where you were part of the hardware design team and you created a PCB and you don't want to have to modify the PCB. Instead, you want to swap the direction by modifying the software – this is your challenge!

I hope this month's topic of analogue inputs and servos has inspired you to explore things further. If you have built the *Micromite Robot Buggy*, then how about trying to make a remote control based on two potentiometers: one for speed, and the other for turning (much like a radio-controlled car). Alternatively, use two potentiometers along with two servos and make a pan/tilt mechanism onto which you could attach a distance module so that you can measure the distance to any object that you are pointing it at.

Next month

One further topic that we have been asked to cover is pulse counting, so next month that is exactly what we will be exploring. Until then, have fun coding!

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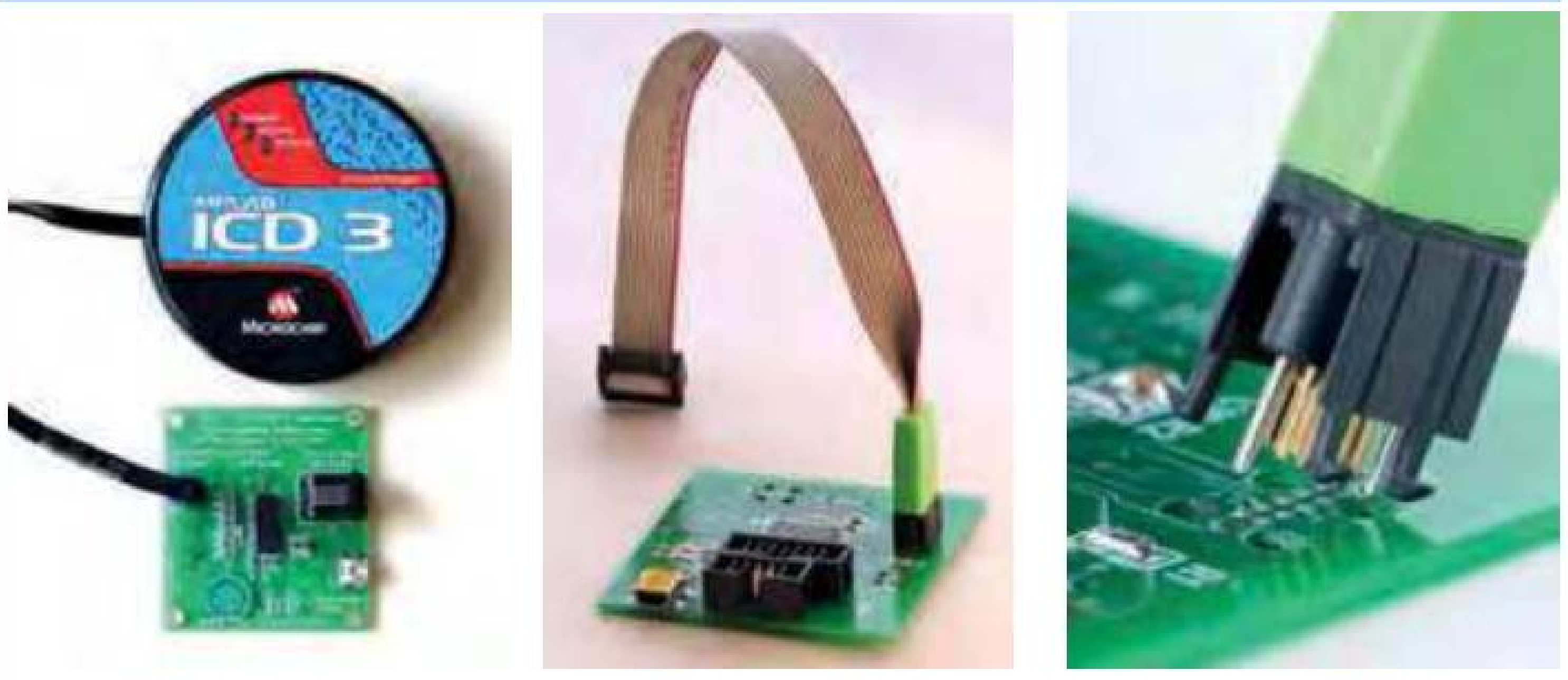

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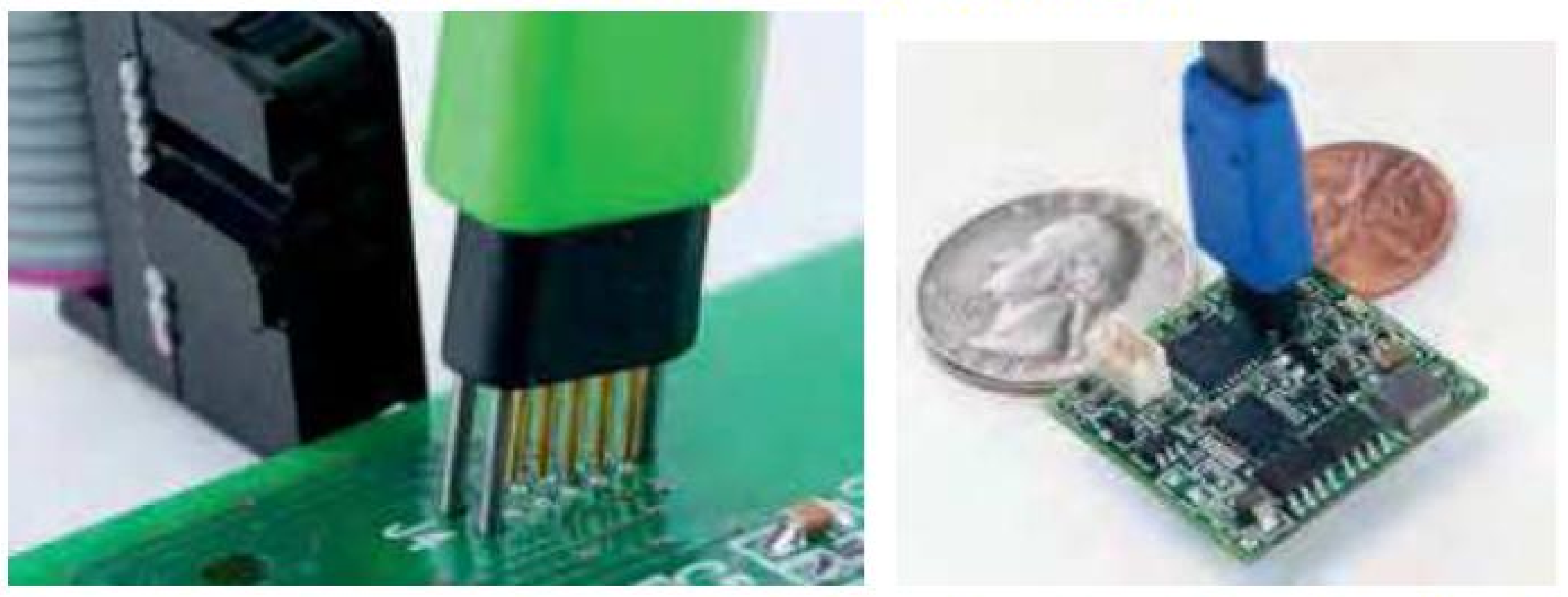

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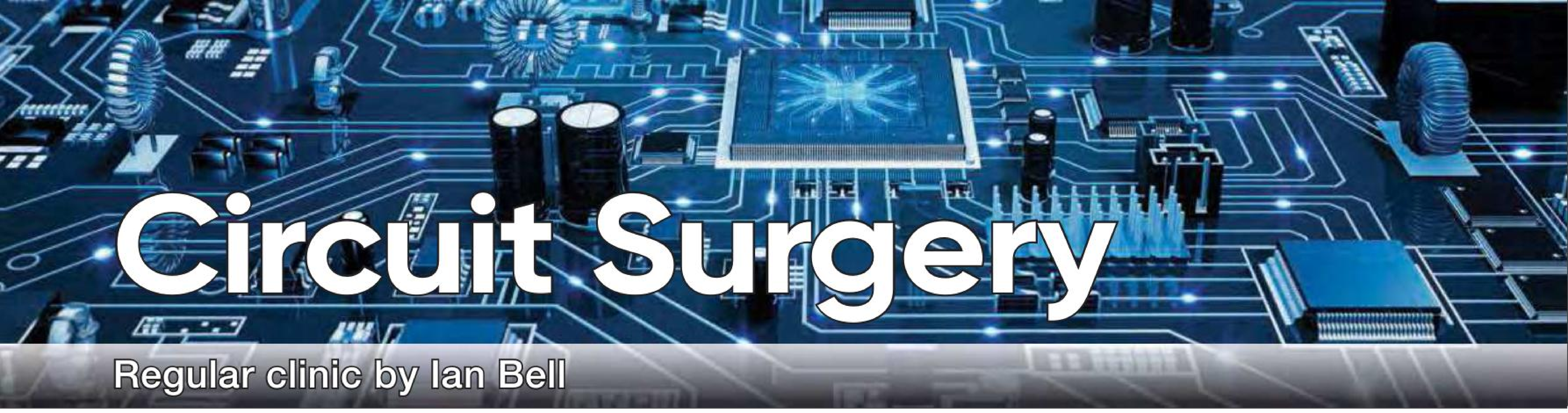


Circuit Surgery

Regular clinic by Ian Bell

Micro-Cap 12 simulator

Circuit surgery articles often include LTspice simulations. Of course, LTspice is not the only SPICE simulator available, however, many require the payment of expensive licence fees. One example of this was Micro-Cap from Spectrum Software, which had been a commercial product for nearly 40 years. Gerald DeSantis emailed *PE* to alert us to the fact that this software, which used to cost $4500, was made available as a free download (for version 12) in July 2019. The owners of Spectrum Software decided to close the business and provide the final version of the software at no cost. We don't know why this happened, but given it has been around for 40 years it may be simply that the developer decided to retire and make the software freely available, rather than just removing it. Various versions are available for download from Spectrum Software (**www.spectrum-soft.com**) but earlier versions (9 and below) still require an existing license security key. Download the 'Full CD' version if you are a new user.

Gerald regards Micro-Cap 12 as one of the best SPICE simulation programs. I was aware Micro-Cap existed but had never had access to a licence. I found that it was easy to download and install but have not had time to evaluated it in detail – so this article is a 'heads up' rather than a review or tutorial, and I will look at a few key features and some very general comparisons with LTspice. I have no reason to believe that it is not very good as Gerald suggests – it certainly seems to be feature rich.

From a quick look, it has a more comprehensive user interface than LTspice, meaning that it might be easier to set up and run simulations which require more user input than just drawing the schematic and hitting the run button. For example, where model parameters have to be changed / set up, or when attempting to optimise component values (eg, stepping through a range of values). Micro-Cap also allows you to control more complex simulations via the menus (we will look at an example of this later).

Library

A plus point for Micro-Cap 12 is that it has a large library of around 45,000 components from a wide range of manufactures. LTspice's library is dominated by Linear Technology and now Analog Devices components (Analogue

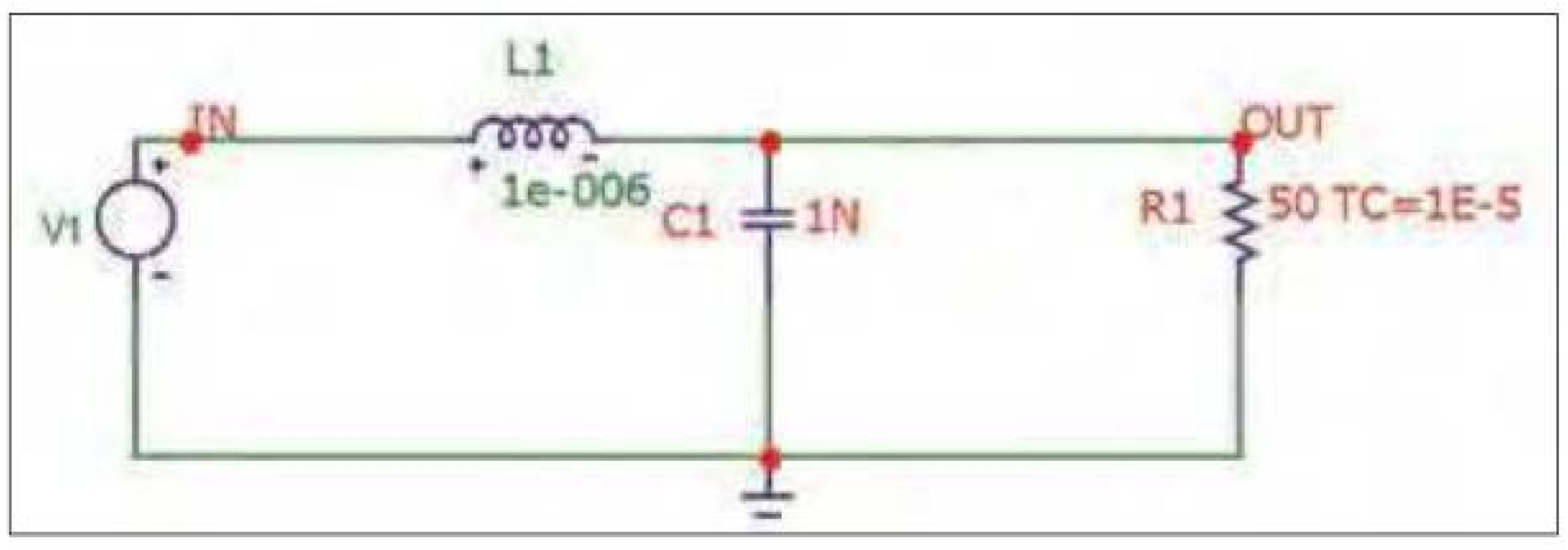
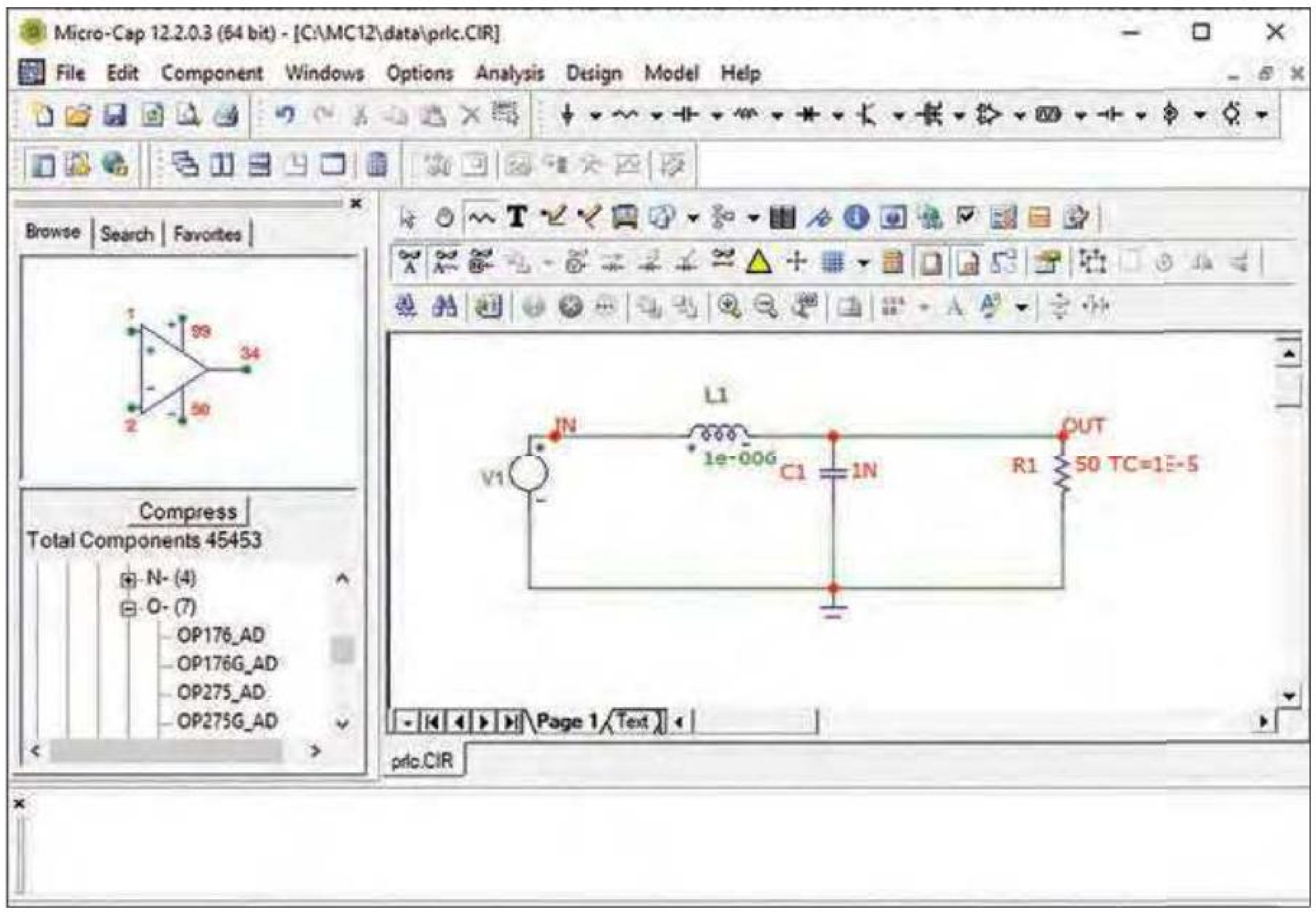

L1
IN
OUT
V1
1e-006
C1
1N
R1
50 TC=1E-5

Fig.1. RLC sample circuit Micro-Cap 12 Schematic.


Micro-Cap 12.2.0.3 (64 bit) - [C:\MC12\data\prlc.CIR]
File
Edit
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Analysis
Design
Model
Help
Browse
Search
Favorites
Compress
Total Components 45453
N- (4)
O- (7)
OP176_AD
OP176G_AD
OP275_AD
OP275G_AD
L1
IN
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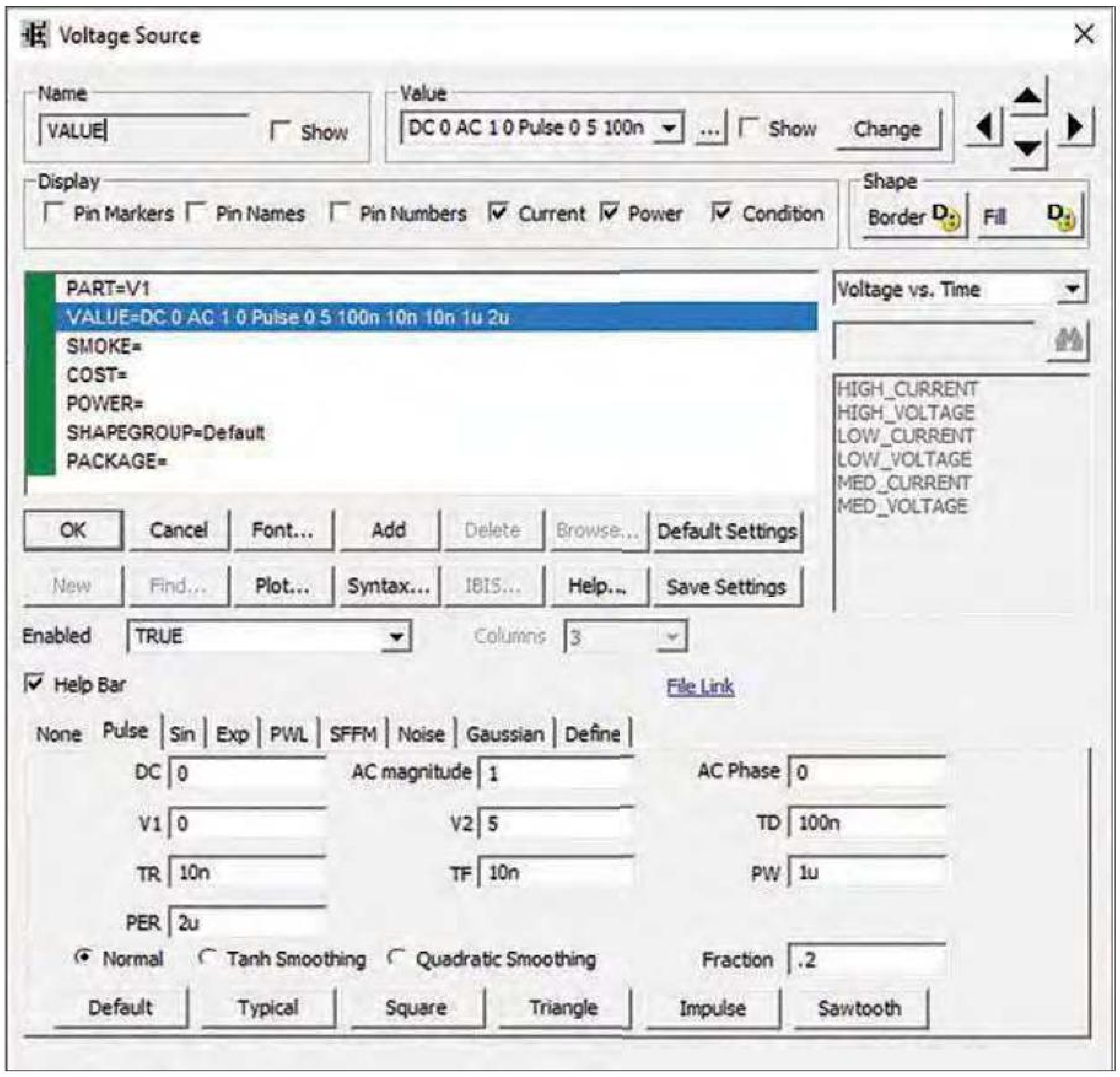
V1
1e-006
C1
1N
R1
50 TC=1E-5
Page 1
Text
prlc.CIR

Fig.2. Full Micro-Cap 12 user interface during schematic editing.


Voltage Source
Show
Change
Display
Shape
Border
Fill
OK
Cancel
Font...
Add
Delete
Browse...
Default Settings
New
Find...
Plot...
Syntax...
IBIS...
Help...
Save Settings
File Link
None
Pulse
Sin
Exp
PWL
SFFM
Noise
Gaussian
Define
Default
Typical
Square
Triangle
Impulse
Sawtooth

Name: VALUE ☐ Show

Value: DC 0 AC 1 0 Pulse 0 5 100n ☐ Show

☐ Pin Markers ☐ Pin Names ☐ Pin Numbers ☑ Current ☑ Power ☑ Condition

PART=V1
VALUE=DC 0 AC 1 0 Pulse 0 5 100n 10n 10n 1u 2u
SMOKE=
COST=
POWER=
SHAPEGROUP=Default
PACKAGE=

Voltage vs. Time

HIGH_CURRENT
HIGH_VOLTAGE
LOW_CURRENT
LOW_VOLTAGE
MED_CURRENT
MED_VOLTAGE

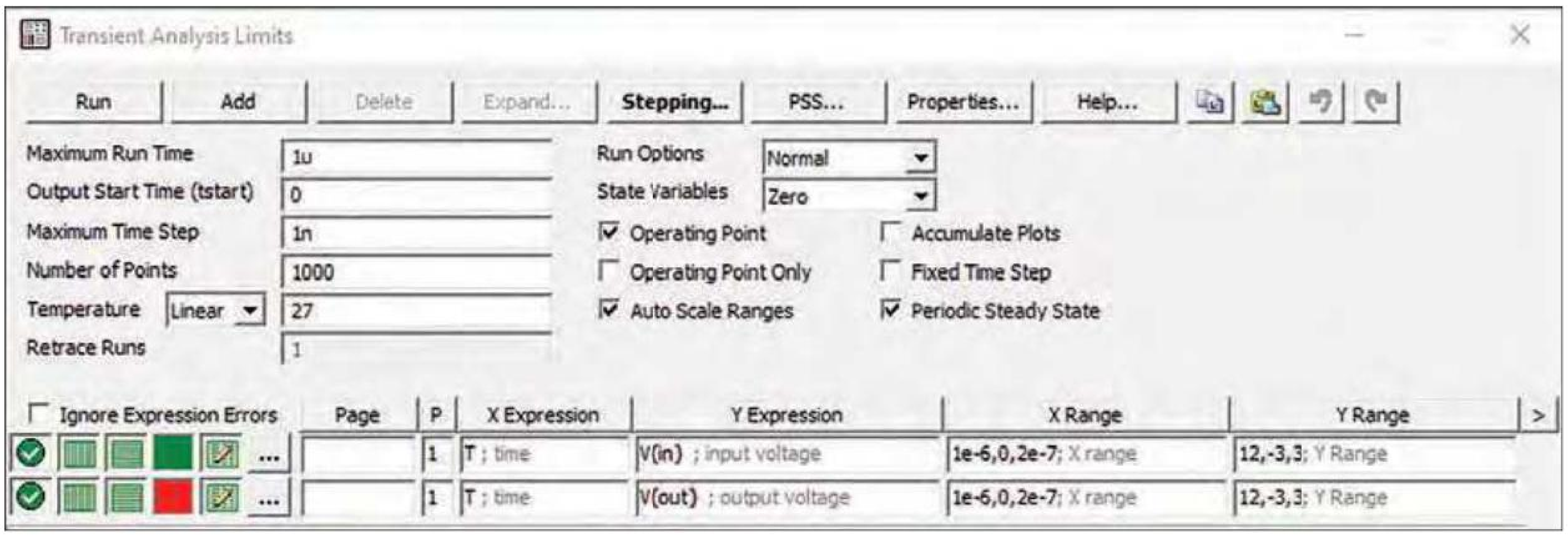
Enabled: TRUE
Columns: 3
☑ Help Bar

DC: 0
AC magnitude: 1
AC Phase: 0
V1: 0
V2: 5
TD: 100n
TR: 10n
TF: 10n
PW: 1u
PER: 2u

● Normal ○ Tanh Smoothing ○ Quadratic Smoothing

Fraction: .2

Fig.3. Component configuration window – this example is to set up the pulse voltage source used in the circuit in Fig.1.



Transient Analysis Limits

Maximum Run Time: 1u
Output Start Time (tstart): 0
Maximum Time Step: 1n
Number of Points: 1000
Temperature: Linear 27
Retrace Runs: 1
Run Options: Normal
State Variables: Zero

☑ Operating Point
☐ Operating Point Only
☑ Auto Scale Ranges
☐ Accumulate Plots
☐ Fixed Time Step
☑ Periodic Steady State
☐ Ignore Expression Errors

Page	P	X Expression	Y Expression	X Range	Y Range
	1	T ; time	V(in) ; input voltage	1e-6,0,2e-7; X range	12,-3,3; Y Range
	1	T ; time	V(out) ; output voltage	1e-6,0,2e-7; X range	12,-3,3; Y Range

Fig.4. Micro-Cap 12 Transient Simulation Set Up Window.

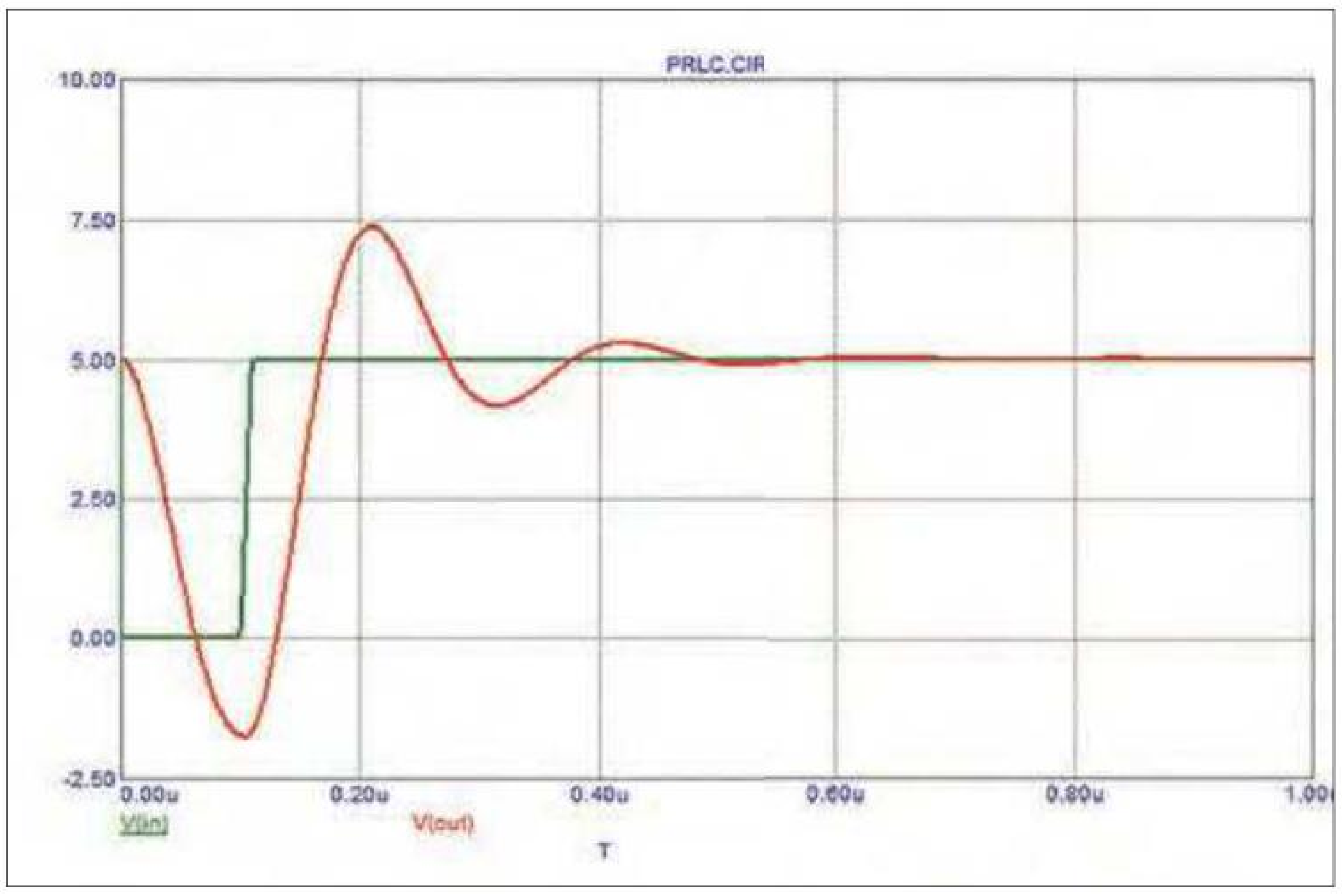


Fig.5. Transient simulation of step input applied to the circuit in Fig.1.

Devices took over LTspice when they acquired Linear Technology in 2017 – it was Linear Technology which created LTspice). This tie to a semiconductor manufacturer's products allows a very high-quality simulator to be made available for free – it does of course help promote Analog/LT products. Devices from other vendors can be simulated in LTspice, but it may require a bit more effort to import the models. Micro-Cap is not device/vendor specific, so it can provide a wide range of models – its business case was not based on device promotion.

Micro-Cap 12's library and simulation capabilities also seem to provide better support for digital circuit simulation (or mixed analogue and digital). LTspice can simulate logic gates and flip-flops, but its capabilities and library are somewhat limited – this is because LTspice is not really aimed at larger digital circuits, its digital capabilities are more focused on tightly coupled mixed analogue and digital. Micro-Cap 12 has a native event-driven digital simulator. It has high, low, rising, falling, unknown and high-impedance logic states and the ability to set the drive strength of outputs to cover situations where multiple outputs are connected together. It has a library of over 2000 standard digital parts, including those from various 4000 and 74 series families.

Maintenance

An obvious potential problem with Micro-Cap 12 is how long it will continue to be usable – if software development has stopped it is likely to become incompatible with up-to-date operating systems at some point. However, it is difficult to predict how long it will last without maintenance (assuming there will be none). Another issue – if you have already spent time learning LTspice (or another simulator) – is the learning curve for a new software package. However, there is a detailed reference manual and a large library of example (sample) circuits which can be opened via the Help menu (sample circuits item). These provide insights into using software features as well some interesting example circuit designs (the LTspice download also includes plenty of examples). As with LTspice, you will find tutorials online. Gerald recommended Kiss Analog's YouTube channel, which has a number of useful videos on Micro-Cap. For anyone interested in analogue circuit design and simulation it is certainly worth investigating.

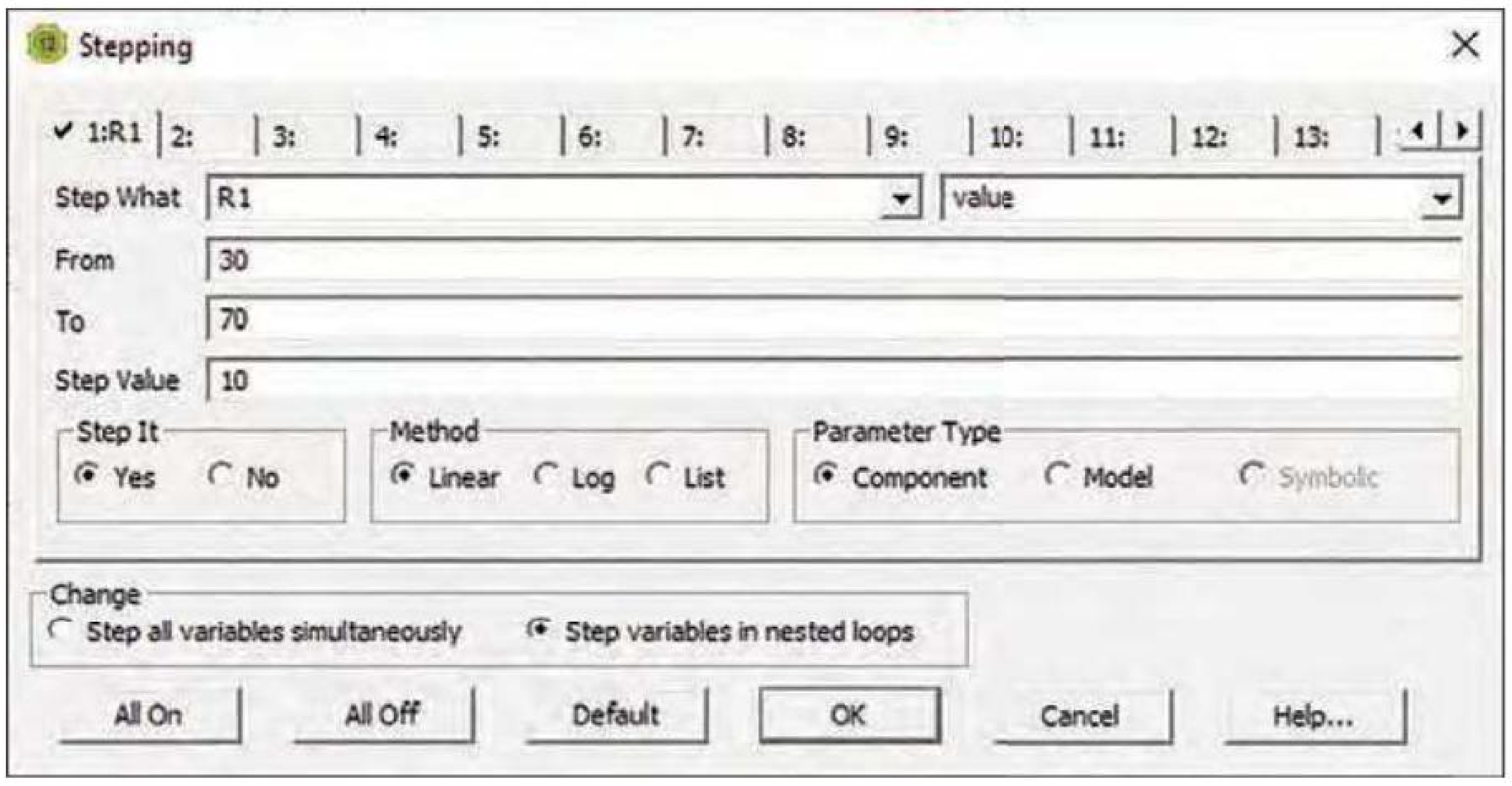
Schematic

An example Micro-Cap 12 schematic is shown in Fig.1 – this is a basic RLC circuit from the sample circuits provided with the download. The schematic editor looks straightforward to use – basic components are available on toolbar buttons, similar to LTspice, and a window to the side of the editor provides access to the large library of components. The screenshot in Fig.2 shows the whole user interface during schematic editing, although this is with the window smaller than you normally use it. In the screenshot, an op amp has been selected from the library and could be added to the schematic.

Double clicking on a component brings up a window which allows it to be configured (values set). Fig.3 shows the window for setting up the voltage source in the circuit in Fig.1. The source is set up to produce pulses with a 1µs duration and a 2µs period, with rise and fall times of 10ns, which start after a delay of 100ns. The screenshot illustrates the detailed and comprehensive nature of the user interface, which seems typical in Micro-Cap 12.

Simulation

Running a transient simulation (Analysis > Transient from the main menu) for the circuit in Fig.1 results in the waveforms shown in Fig.5. The sample circuit transient analysis set-up initially only shows the output wave (red), but it is straightforward to add the input wave (green) to the plot when selecting the transient simulation – see Fig.4. The Add button allows additional plots and traces to be added, with details entered in the table at the bottom of the window. When the set-up is run the Run button starts the simulation, producing the results shown in Fig.5. The simulation is configured to run for 1µs (see max run time in Fig.4) so we only see the first edge of the initial pulse. Double clicking the trace names allows many things to be configured, such as line colour and thickness.



Stepping

Step What: R1 value
From: 30
To: 70
Step Value: 10

Step It: ● Yes ○ No
Method: ● Linear ○ Log ○ List
Parameter Type: ● Component ○ Model ○ Symbolic
Change: ○ Step all variables simultaneously ● Step variables in nested loops

Fig.6. Interface for setting up value stepping in a simulation.

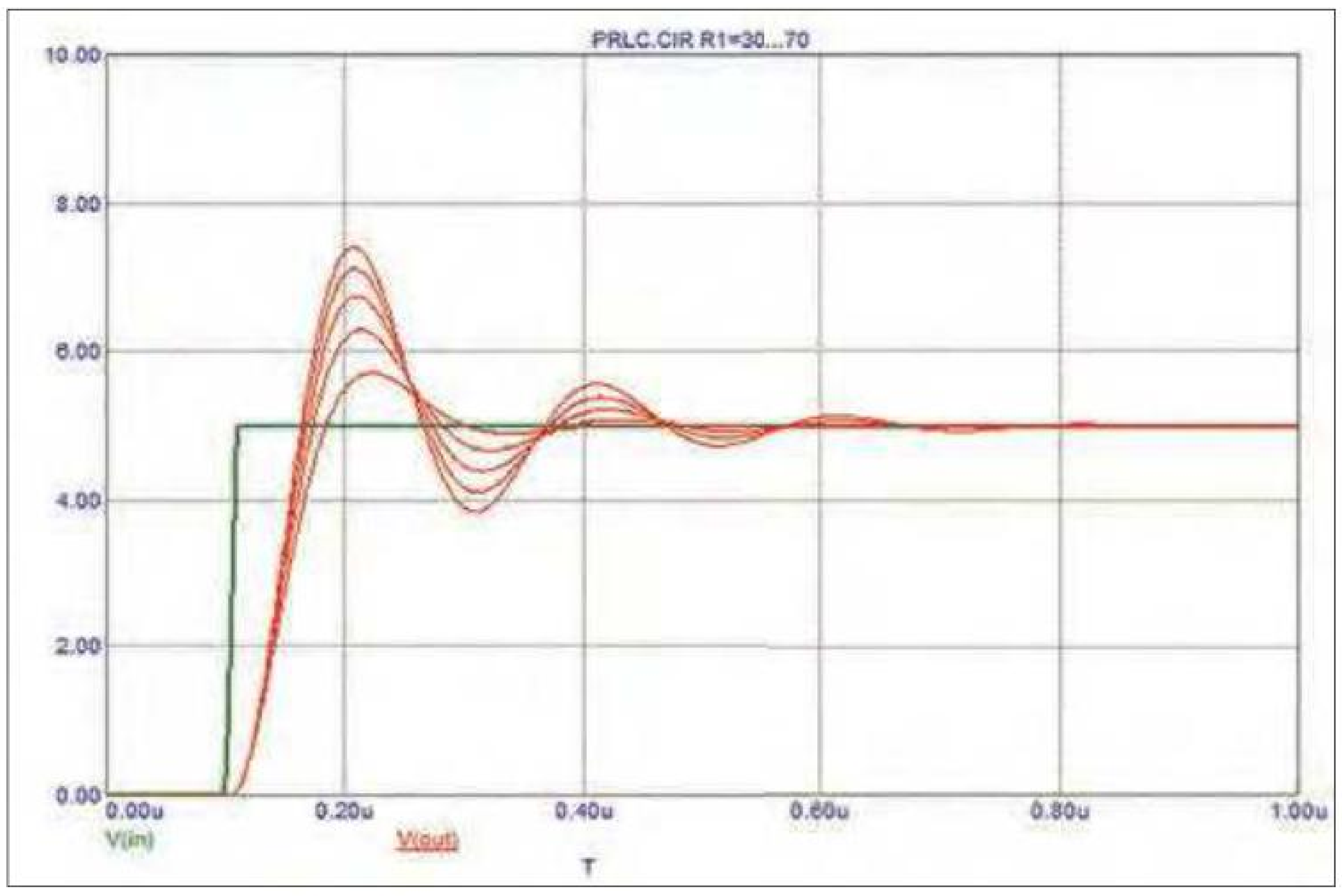
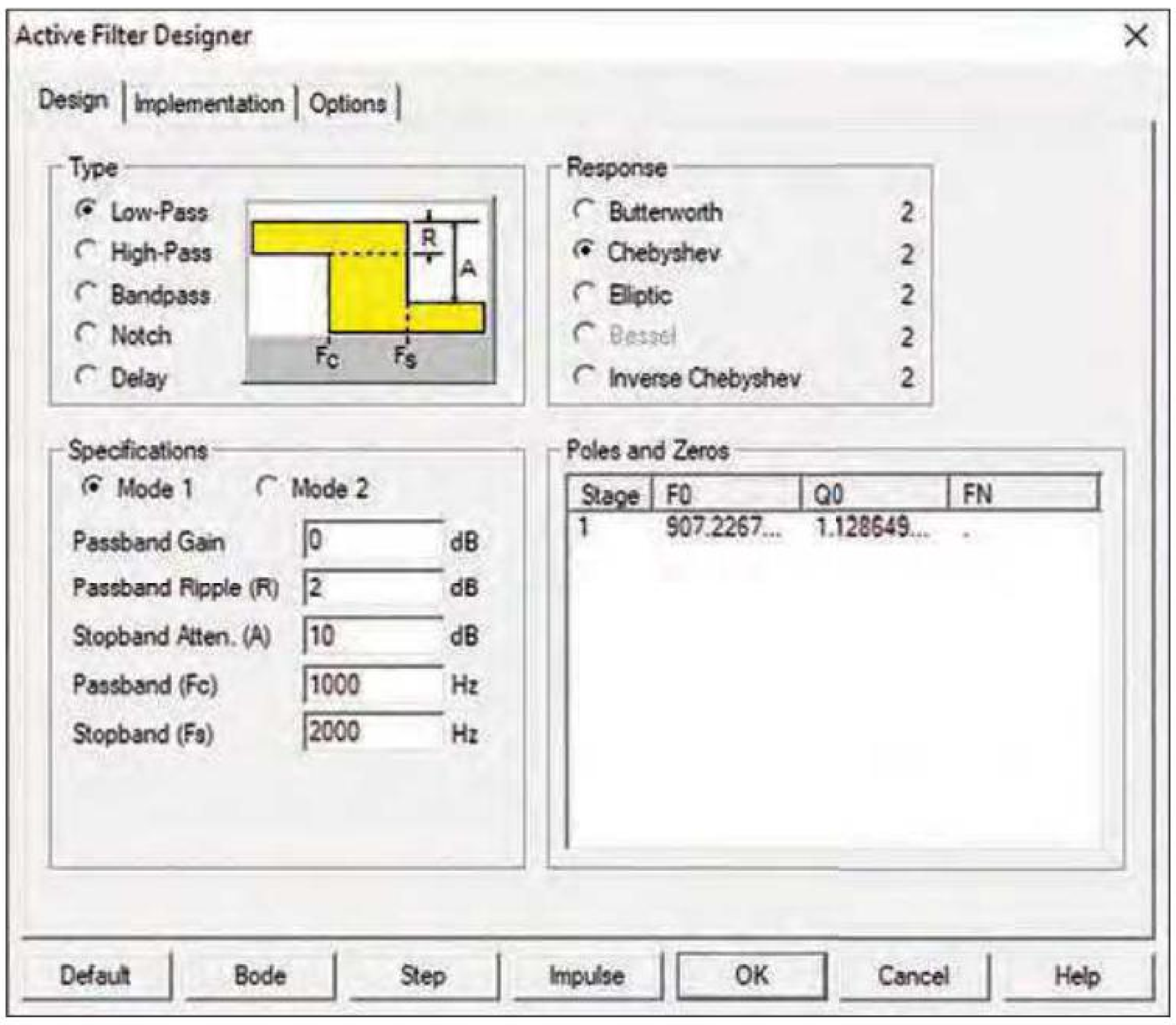


Fig.7. Transient simulations with value of R1 in Fig.1 stepped from 30Ω to 70Ω in steps of 10Ω.

The basic simulation described so far more or less parallels the same process in LTspice. However, as mentioned earlier Micro-Cap 12 provides some more capabilities directly via menus. One example of this is component value stepping. This is a useful process which enables a designer to quickly investigate the effect of changing a circuit parameter on its performance or behaviour. For example, we might want to investigate the effect of varying the resistor (R1) value on the shape of the output waveform for the circuit in Fig.1. To do this in LTspice we have to write a text command (SPICE directive) to define a parameter for the resistor value and another to configure the stepping. It is not particularly difficult, but it is less obviously available and less convenient to quickly alter than the dialog window for the same purpose provided by Micro-Cap 12 (see Fig.6). This can be accessed by clicking the Stepping button in transient simulation set-up, or from the Transient menu after the simulation has been run.

Fig.6 shows R1 set up to be stepped from 30Ω to 70Ω in 10Ω steps. The 'Step It' check box has to be on for the stepping to be applied. The tabs in the window allow more values to be selected for stepping. The results of running the simulation with the stepping set up are shown in Fig.7. There are multiple traces for V(out) corresponding with the various R1 values. Hovering the cursor over any of the traces produces a 'tooltip'-type box which informs you of the relevant R1 value. Stepping can be used to help quickly select the best component value if you are not certain what to use, or do not know how, or are too lazy to calculate it.



Type
● Low-Pass
○ High-Pass
○ Bandpass
○ Notch
○ Delay

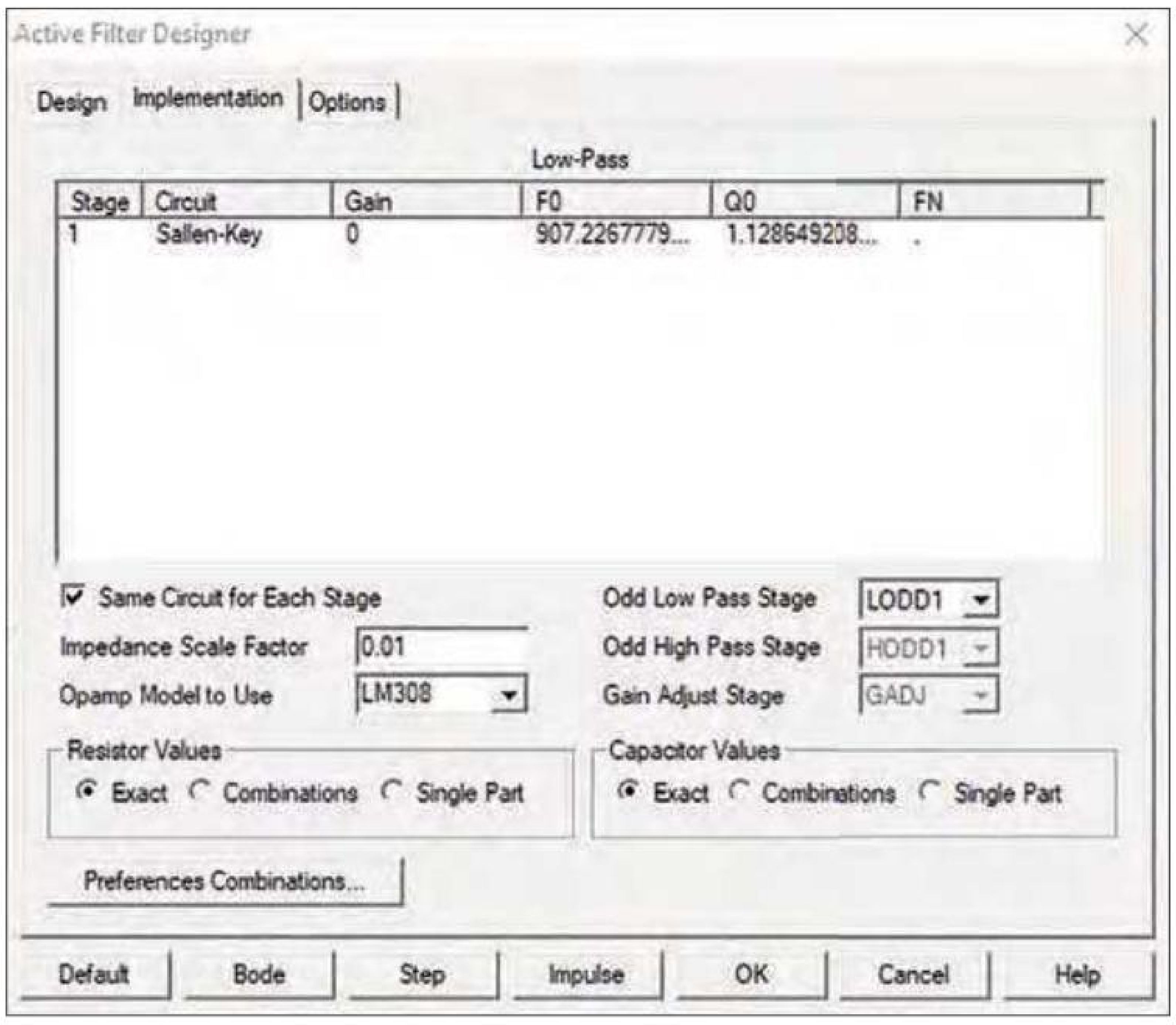
Response
○ Butterworth 2
● Chebyshev 2
○ Elliptic 2
○ Bessel 2
○ Inverse Chebyshev 2

Specifications
● Mode 1 ○ Mode 2
Passband Gain 0 dB
Passband Ripple (R) 2 dB
Stopband Atten. (A) 10 dB
Passband (Fc) 1000 Hz
Stopband (Fs) 2000 Hz

Poles and Zeros

Stage	F0	Q0	FN
1	907.2267...	1.128649...	.

Fig.8. Filter Designer with design settings for a Chebyshev low-pass filter.



Low-Pass

Stage	Circuit	Gain	F0	Q0	FN
1	Sallen-Key	0	907.2267779...	1.128649208...	.

☑ Same Circuit for Each Stage
Impedance Scale Factor 0.01
Opamp Model to Use LM308
Odd Low Pass Stage LODD1
Odd High Pass Stage HODD1
Gain Adjust Stage GADJ

Resistor Values
● Exact ○ Combinations ○ Single Part

Capacitor Values
● Exact ○ Combinations ○ Single Part

Fig.9. Filter Designer implementation settings – note scaling factor and op amp choice.

Another design procedure related to value stepping is Monte Carlo simulation. This varies selected component and model values statistically to simulate the normal variation in values inherent in manufacturing processes. As many of you will have guessed, the name is inspired by the fame of Monte Carlo's casinos (another statistical process!). This can be used to check that the performance of mass-produced circuits (particularly integrated circuits) will be within specifications given the variations present in the components ('process variations' in integrated circuit terminology). It is more complex to set up than stepping and we will not go into the details here. Like stepping, both LTspice and Micro-Cap 12 can perform Monte Carlo simulation, but again, Micro-Cap 12 has dialogs to help set it up, whereas with LTspice you have to use text commands (you can also write text commands in Micro-Cap 12). Furthermore, if you search LTspice's help you will not find anything about Monte Carlo simulation, but Micro-Cap 12 has plenty of entries. Of course, you can find

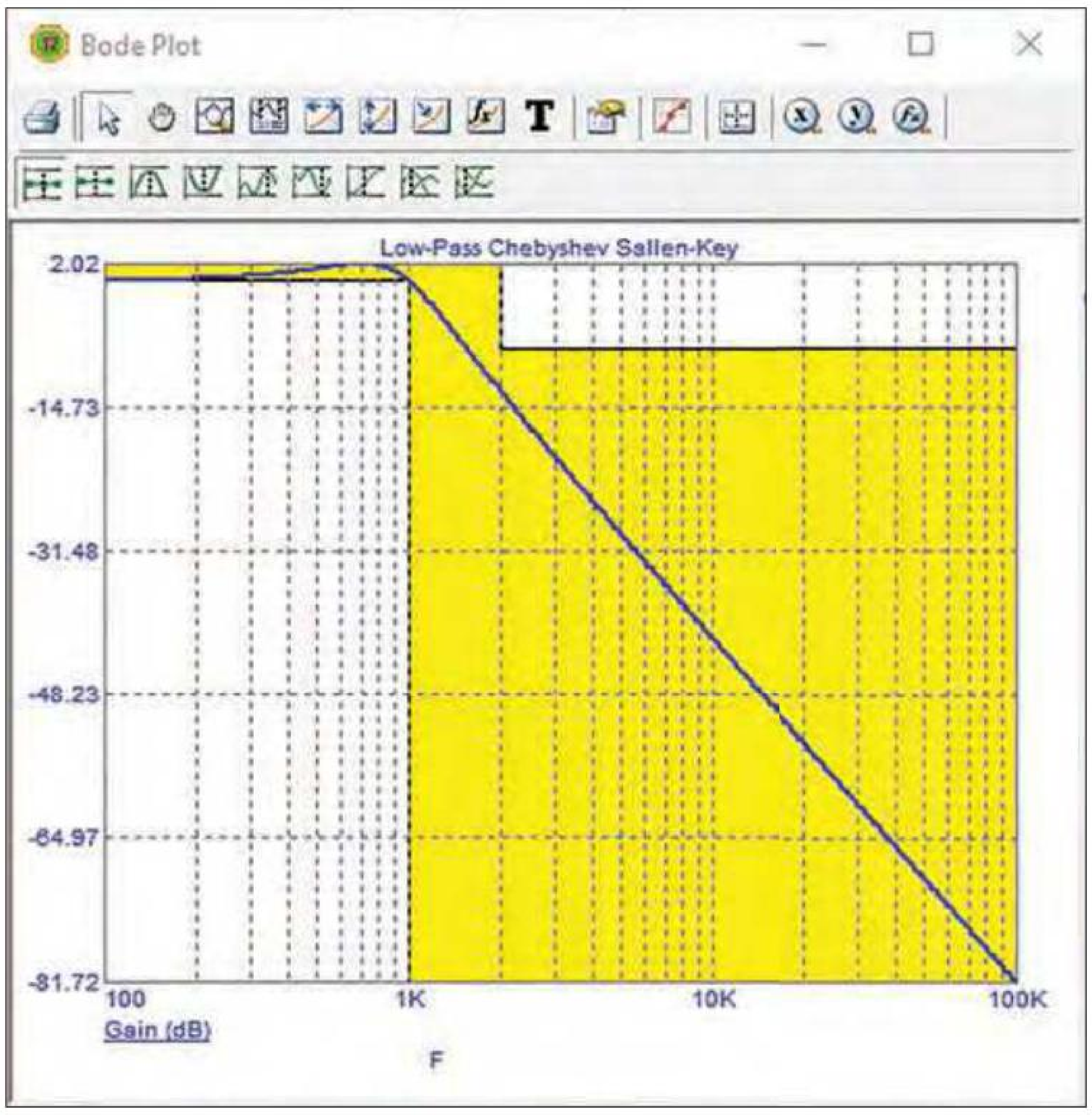


Fig.10. Idealised frequency response for the filter design from Fig.8 and 9.

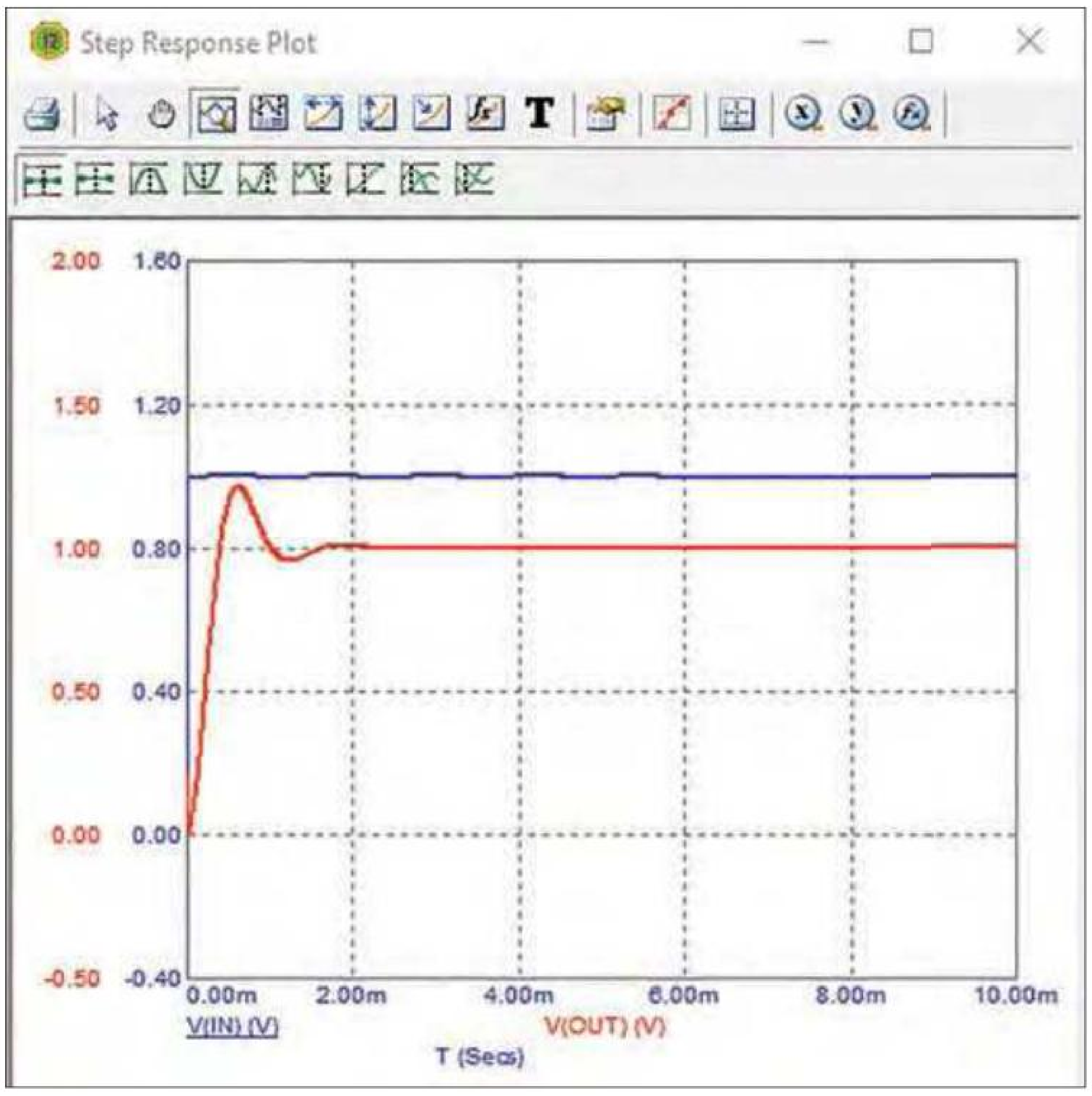


Fig.11. Idealised step response for the filter design from Fig.8 and 9.

the LTspice instructions online, but the lack of comprehensive built-in help can be difficult when first using LTspice.

Filter Design

Micro-Cap 12 includes a filter design facility (Design > Active Filters or Passive Filters from the menu). This enables you to specify the filter requirements, from which it can create filter schematics. It is potentially very useful and there is nothing like it in LTspice, which is focused on simulation, rather than other design tools. The Micro-Cap 12 Filter Designer can produce all the basic types (low-pass, high-pass, bandpass…) with various responses (eg, Butterworth, Chebyshev, Bessel) and in a variety of implementations (passive filters and active filters such as Sallen-Key, MFB, Tow-Thomas...). Not all combinations are possible because not all filter types can produce the whole list of response types.

The Active Filter Designer dialog has three settings tabs to configure the filter requirements and options. Fig.8 shows an example set up for a 1.0kHz, low-pass, Sallen-Key Chebyshev filter with 2dB pass-band ripple. The diagram next to the filter-type selection defines the parameters which are used to specify the filter. The default circuit uses 10nF and 100pF capacitors, which results in large resistor values. The next tab – implementation (see Fig.9) – allows you to change the Impedance Scale Factor (here it was changed from 1 to 0.01), which multiplies all resistor values and divides all capacitor values to help set practical values. You can also choose the op amp (ideal or real devices – an LM308 is selected in Fig.9) and various other things. The options tab provides yet more choices such as display formats for component values.

Clicking the buttons at the bottom of the Active Filter Designer dialog allows you to see idealised frequency (Bode), step and impulse response curves for the filter. The Bode plot is a graph of gain against frequency. The step response is the output produced by an instantaneous voltage step at the input from 0V to 1V. The impulse response is the output produced by a pulse from 0V to 1GV and lasting 10^{-9} seconds (ideally it has an amplitude that tends to infinity and a duration that tends to zero, but the area under the pulse is 1). Impulse responses are important in the mathematical analysis of filters.

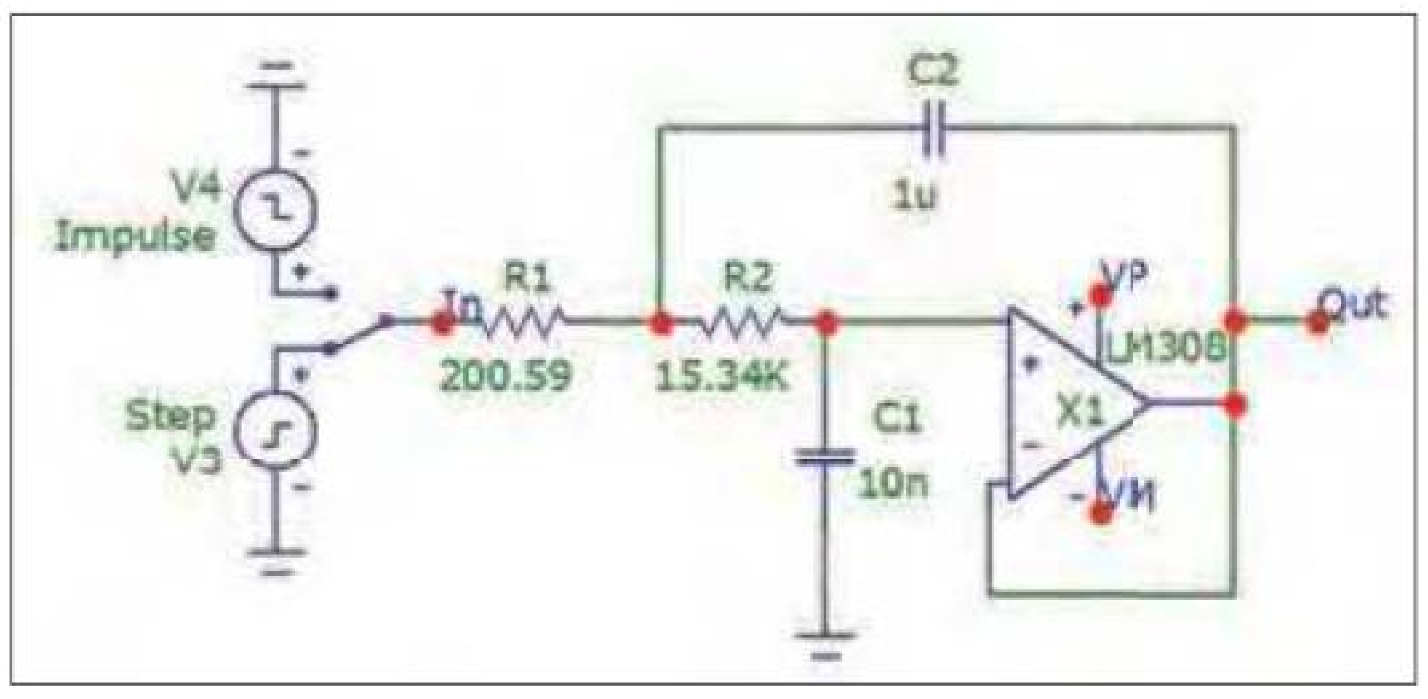


Fig.12. Schematic created by the Filter Designer.

Fig.10 and 11 show examples of the Bode and steps plots. These graphs are based on the standard polynomial formula for the selected filter response and will only be produced by ideal circuits. The filter designer creates a circuit schematic which contains models of real components (eg, the specified op amp device) – for example see Fig.12. The schematic was produced by selecting the 'Circuit' rather than 'Macro' option in the options tag – this is simpler to work with for a quick simulation than the hierarchical schematic created by the default macro option.

Filter Simulation

Fig.13 shows a frequency response (AC analysis) for the circuit in Fig.12. The analysis is run from the main menu and starts with a dialog similar to Fig.4 for the transient analysis. The frequency range may need to be changed (from the default) in the AC analysis dialog to one suitable for the filter being investigated. Here, 100Hz to 100kHz was selected to match Fig.9.

The switch in Fig.12 illustrates another feature of Micro-Cap 12 – dynamic simulation updates. Double clicking the switch changes its position and reruns the analysis with the new situation. In this case it makes no difference because the two pulse sources behave the same for an AC analysis, but in general it is a useful facility.

From Fig.13 we see that the real circuit does not have the same frequency response as the ideal filter (shown in Fig.10). The response is fine until just over 10kHz, at which point the gain starts rising rather than continuing to fall, as it does in the ideal case. This is a known issue with Sallen-Key filters and is related to changes in output impedance as frequency increases. Here it serves as a nice illustration of the process of using the Filter Designer – we quickly check the ideal response to make sure that the design values were entered correctly and then simulate a more realistic version of the circuit. In this example, if the response shown in Fig.13 is not adequate, we could select a different op amp or run the filter designer again using a different implementation, such as MFB (multiple feedback), which is less susceptible to the observed problem.

Features

We have only looked at a few of the features of Micro-Cap 12 in this article. Some others include – 'smoke analysis', which looks at maximum operating values; optimisers for maximising circuit performance; analogue behavioural modelling (we looked at this for LTspice in August 2020); 3D plots; animated schematics with graphical objects such as meters and seven-segment displays; and netlist export to some PCB design tools. For a quick run through these, and other capabilities, take a look at the 'Features Tour' on the Spectrum Software website.

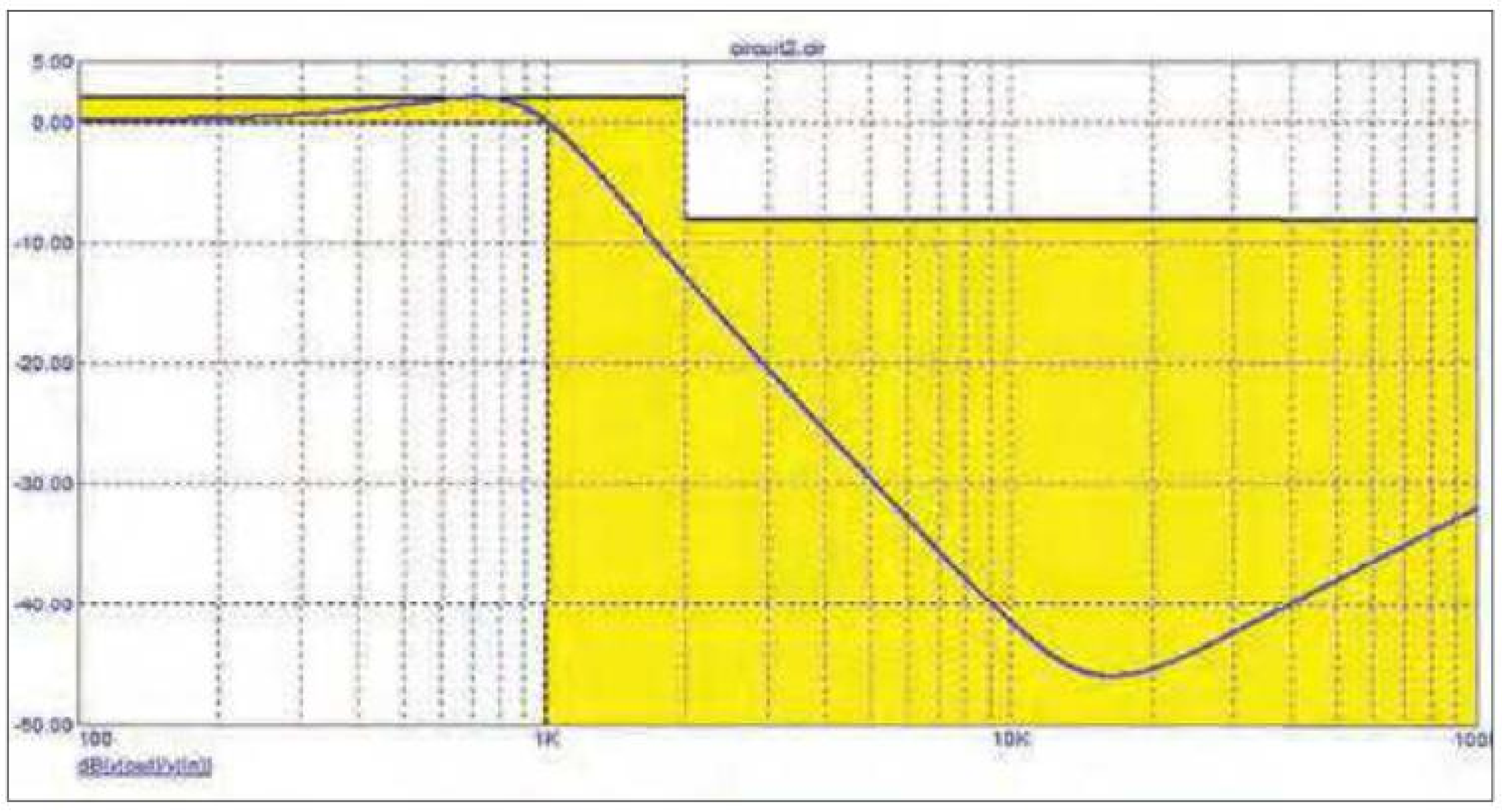


Fig.13. Simulation of the circuit in Fig.12 – compare with the ideal response in Fig.10.

Max's Cool Beans

By Max the Magnificent

Flashing LEDs and drooling engineers – Part 10

Well hello there. I hope you're having as awesome a day when you read this as I'm having while I write it. Just to make sure we are all tap-dancing to the same 'skirl of the pipes*,' let's briefly remind ourselves that we are currently playing with a 12x12 array of ping-pong balls, each containing a WS2812-based tricolour LED (*I know whereof I speak, because my dear old dad was a dancer on the variety hall stage prior to WWII, and he was in the Reconnaissance Unit of the 15th Scottish Infantry Division during WWII, as part of which he earned many beers performing Scottish sword dances to the sound of the bagpipes).

For the past few columns, we've been experimenting with 'virtual drips' randomly falling on, and lighting up, pixels in our array. At the end of our previous column (*PE*, November 2020), we noted that – up until now – we've worked with only a single drip at a time (Fig.1a). We also conjectured that it would be more exciting if we were to allow multiple drips to be active concurrently, and for their start and end times to be randomly determined such that they overlap in interesting and unpredictable ways (Fig.1b).

Like most things, of course, implementing a cornucopia of contemporaneous drips sounds easy if you say it quickly and gesticulate furiously. Sad to say, however, the underlying way in which we've been implementing things in our code thus far will prove to be rather limiting. But turn that frown upside down and into a smile, because we won't let anything prevent us from achieving our multi-drip extravaganza, or my name isn't Max the Magnificent.

In a bit of a state

Consider the following interpretation of the main `loop()` function used in the Arduino's classic 'Blink' sketch (program). Let's assume we are using this program to control a yellow LED. In this particular example, we are cycling around turning the LED on and off at a frequency of 1Hz (one cycle per second).

```
void loop()
{
   digitalWrite(PinLed,  LOW);
   delay(500);
   digitalWrite(PinLed, HIGH);
   delay(500);
}
```

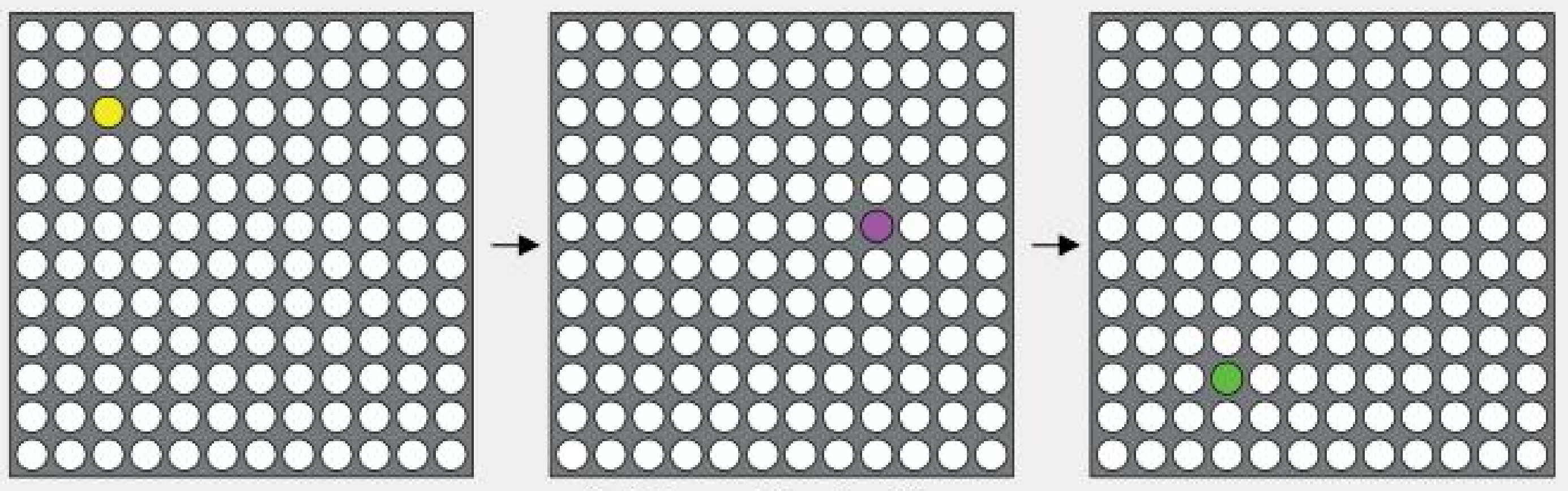
The term 'finite-state machine' (FSM), or simply 'state machine', refers to a mathematical model of computation. The underlying idea is that we have an abstract machine that can be in only one of a finite number of states at any particular time. The reason I mention this here is that the code presented above might be considered to implement a rudimentary state machine, whose operation we could depict graphically as illustrated in Fig.2a.

Now, suppose we decide to add a red LED, and have the two LEDs turning on and off at different rates. Let's say the red LED has a frequency of 1Hz, while the yellow LED has a frequency of 2Hz. The main `loop()` code for this could be as follows, with a graphical equivalent as depicted in Fig.2b (the full sketch is presented in file **CB-Dec20-01.txt** – it and the other files associated with this article, are available on the December 2020 page of the *PE* website).

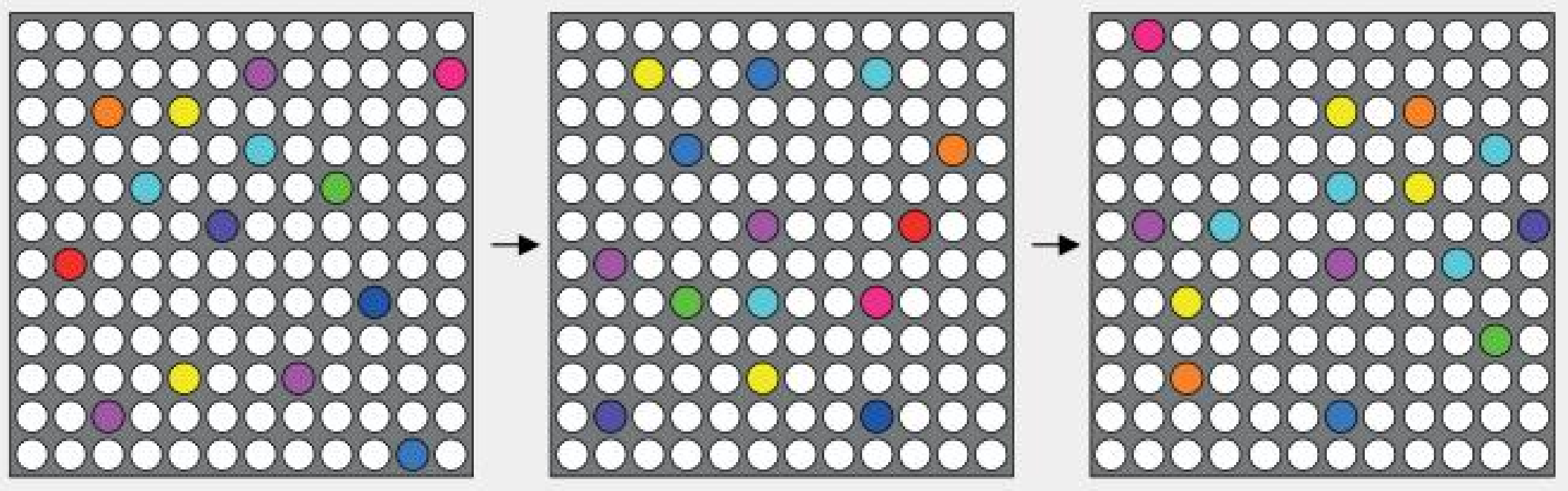
```
void loop ()
{
   // State 0
   digitalWrite(PinRedLed,     LOW);
   digitalWrite(PinYellowLed,  LOW);
   delay(250);

   // State 1
   digitalWrite(PinRedLed,     LOW);
   digitalWrite(PinYellowLed, HIGH);
   delay(250);

   // State 2
   digitalWrite(PinRedLed,    HIGH);
   digitalWrite(PinYellowLed,  LOW);
   delay(250);

   // State 3
   digitalWrite(PinRedLed,    HIGH);
   digitalWrite(PinYellowLed, HIGH);
   delay(250);
}
```

In a classic FSM, we would have some way to remember the current context (state) of the machine. This could be a register containing the state variables in the case of a hardware implementation, or an enumerated type in the case of a software realisation (see this month's *Tips and Tricks* column for more information on enumerated types). By comparison, when it comes to our example code shown above, apart from using comments, we don't have any way to explicitly define the current state. Instead, the state is implied by where we are in the code.

In order to illustrate why this is a problem, let's suppose I were to ask you to add a green LED with a frequency of 3Hz into the mix. Take a moment to think about how you would implement the



(a) One drip at a time



(b) Multiple drips at the same time

Fig.1. Single versus multiple drips.

code for this. I can imagine you smiling because, even though you know that everything is so intertwined it will undeniably make things trickier, you are sure that – if push came to shove – you could do this. How about if, instead of simply turning the three LEDs on and off, I ask you to fade them on, hold them steady, and fade them off, with each fade taking 10 steps over 100 milliseconds (ms). You aren't smiling now, are you?

When we come to think about it, this is pretty much where we are with our existing drip programs. Although it's true that we've implemented some very tasty fading effects using different colours, we've only achieved this with one drip at a time. We're going to have to adopt a new approach if we wish to have multiple drips active concurrently in random relationships to each other.

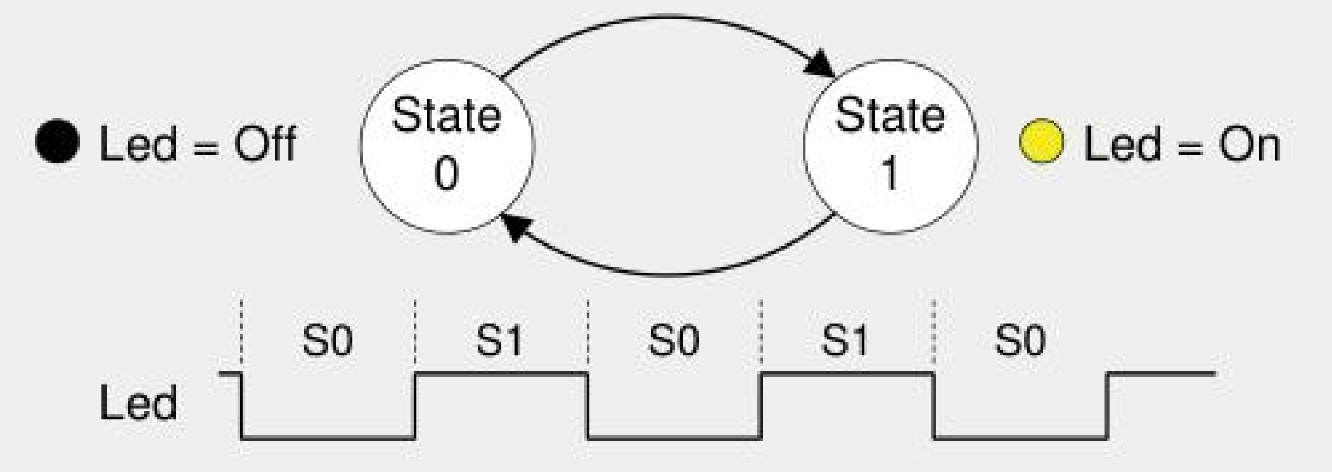
Dump the `delay()`!

The `delay()` function shown in the code examples above is a blocking function, which means it completely ties up the processor, thereby preventing (or blocking) anything else from happening. While the processor is executing a `delay()`, it can't respond to changes on any of its inputs, it can't perform any calculations or make any decisions, and it can't change the state of any of its outputs.

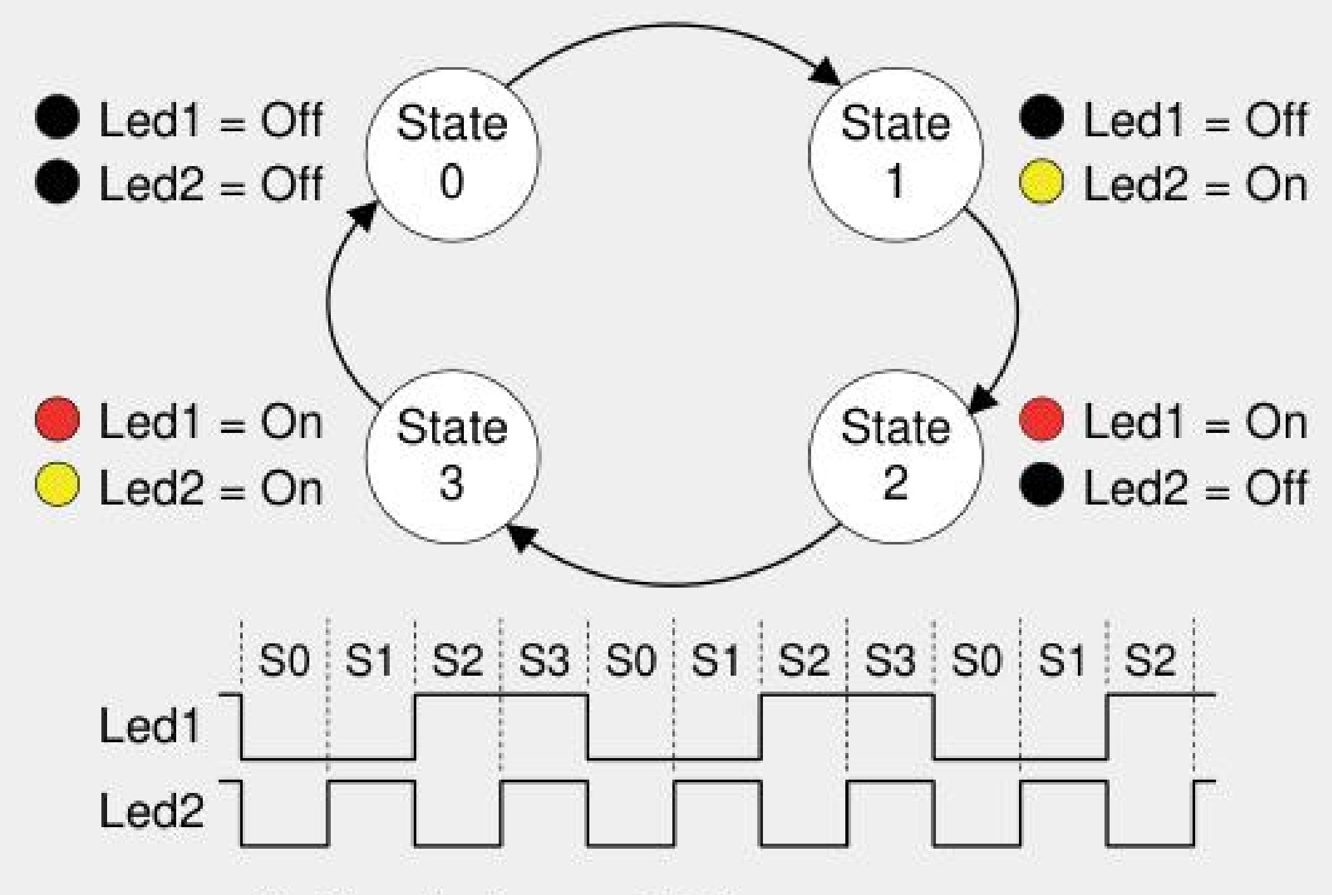
The bottom line is that, in order to achieve multiple drips, we need to dump the `delay()` and implement our code using some other approach. One technique we can employ is to cycle around checking the system clock to determine when it's time to act. Let's look at a simple example of this in action. What we are going to do is create a new version of our 2-LED program using this new method. As you will see if you look at the code (file **CB-Dec20-02.txt**), we start by defining `LED_OFF` and `LED_ON` as `LOW` and `HIGH`, respectively. We also declare two global variables `StateRedLed` and `StateYellowLed` to hold the current states (`LED_OFF` or `LED_ON`) of their respective LEDs.

For the purposes of these examples, each LED has a 1:1 mark-space ratio, which means it's on for the same amount of time as it's off. Since we wish the red LED to have a frequency of 1Hz, which equates to a period of 1,000ms, this means it will alternate between being on for 500ms and off for 500ms. Similarly, as we wish the yellow LED to have a frequency of 2Hz, which equates to a period of 500ms, this means it will alternate between being on for 250ms and off for 250ms.

All of this explains why we declare a global variable called `OnOffDelayRedLed`, which we set to 500ms, and a global variable called `OnOffDelayYellowLed`, which we set to 250ms. Furthermore, we also declare two global variables `LastTimeRedLedChanged` and `LastTimeYellowLedChanged`, which – as their names suggest – we will use to keep track of the last time their associated LEDs changed state.



(a) Simple 2-state FSM



(b) Simple 4-state FSM

Fig.2. Simple state machines

The code for the first half of the main loop is shown below. We start by loading the local variable `currentTime` with the value returned from the Arduino's `millis()` function, which will be a 32-bit unsigned integer representing the number of milliseconds that have passed since the Arduino powered up and the program started running.

```
void loop ()
{
   uint32_t currentTime = millis();

   if ( (currentTime - LastTimeRedLedChanged) >=
           OnOffDelayRedLed )
   {
      if (StateRedLed == LED_OFF)
      {
         StateRedLed = LED_ON;
      }
      else
      {
         StateRedLed = LED_OFF;
      }

      digitalWrite(PinRedLed, StateRedLed);
      LastTimeRedLedChanged = currentTime;
   }

   // More code goes here
}
```

Next, we perform a test to see if the current time minus the last time the red LED changed is greater than or equal to the red LED's on/off delay, which we previously set to 500ms. If not, we don't do anything. However, if it has been 500ms or more since the red LED changed, we flip its state (from off to on, or vice versa), then we write this new state to the pin driving the red LED and we reset the variable storing the last time this LED changed state to be the current time.

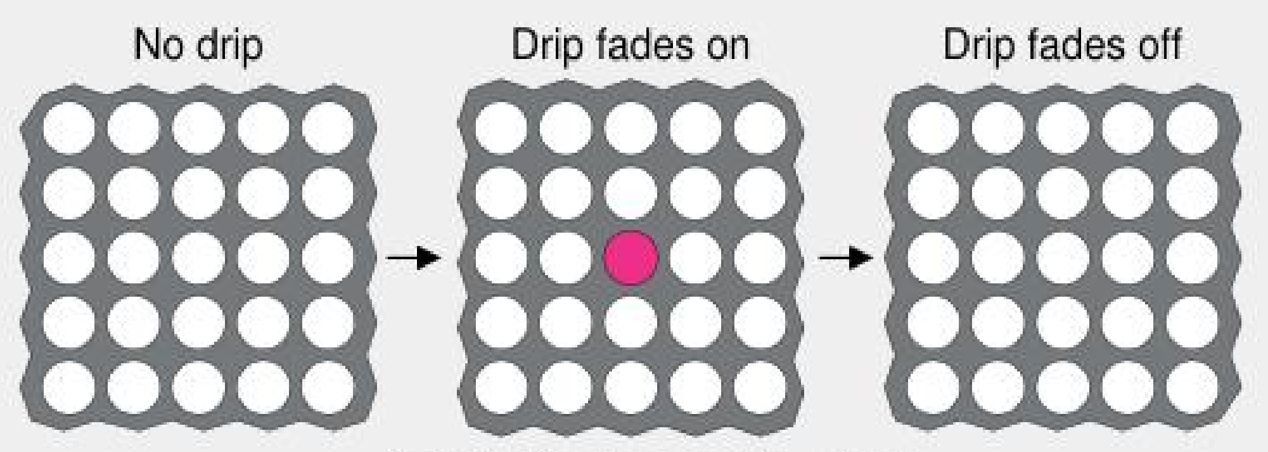
Your first reaction may be to scream 'Arrgggh!' Your second reaction may be to say in menacing tones, 'Forgive me for saying so, but this appears to be a tad more complicated than simply using calls to the `delay()` function.' Well, yes and no. Although this takes a little more effort to set up, it makes our lives a lot easier in the long run. For example, the code to handle the yellow LED (which will appear where we show the '// More code goes here' comment) is simply a modified copy of the `if ()` statement we used to handle the red LED. Similarly, if we decided to add a green LED with a frequency of 3Hz, all we would need to do would be to add `StateGreenLed`, `OnOffDelayGreenLed`, and `LastTimeGreenLedChanged` global variables and also add a new `if ()` statement into our main loop. Trust me – the more you think about this, the easier it gets.

My register floweth over

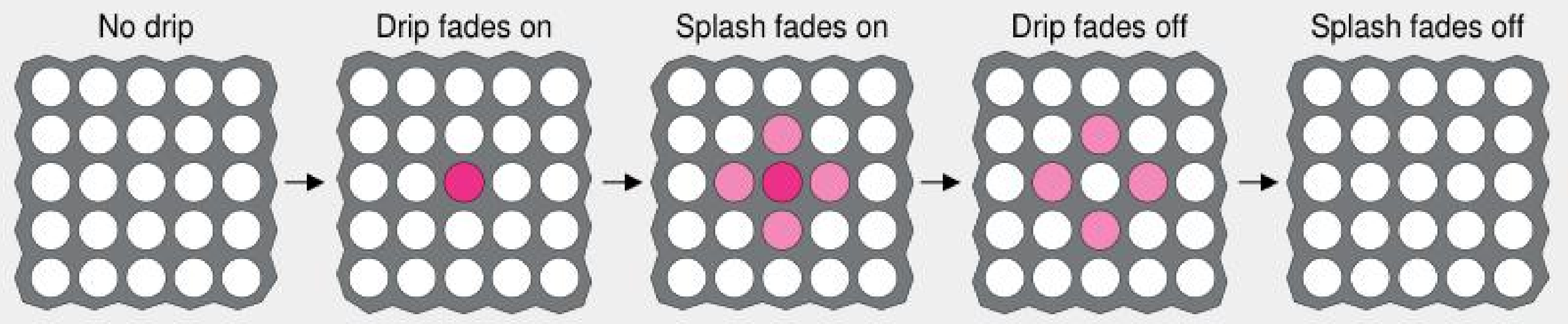
Earlier, we noted that the Arduino's `millis()` function returns a 32-bit unsigned integer representing the number of milliseconds that have passed since the Arduino powered up and the program started running.

This value is stored in a 32-bit counter/timer register buried deep in the Arduino's internal architecture. One question you were doubtless asking yourself is, 'What happens when this register overflows?' By this we mean that when we power up the Arduino, this register contains 0 (or 0x00000000 in hexadecimal). If we keep on incrementing this register every millisecond, then it will eventually contain 2^{32} = 4,294,967,296 (or 0xFFFFFFFF in hexadecimal).

How long will this take and what happens next? Well, since the register increments every millisecond (one thousandth of a second), we can divide 4,294,967,296 by 1,000 to get seconds, then divide by 60 to get minutes, and by 60 again to get hours, and by 24 to get days. By this, we discover that it will take close to 50 days before the register fills up.



(a) Rudimentary drip effect



(b) Augmenting each drip with an associated splash

Fig.3. Rudimentary drip effect compared to a 'drip plus splash' effect.

Once the register contains 4,294,967,296 (0xFFFFFFFF), the next tick of the millisecond clock will cause it to overflow and return to containing 0 (0x00000000), and we start all over again.

So, when we pass through this wraparound case, what will happen to our test (`currentTime – LastTimeRedLedChanged) >= OnOffDelayRedLed`)? Might we see a glitch or something worse? On the one hand, it's unlikely that we will be running our drip program for 50 days or more at a stretch. Also, the world wouldn't end if there were a glitch in an application of this ilk. On the other hand, suppose we wished to use a similar technique to control a safety-critical or mission-critical system in which any form of glitch, no matter how slight, would not be considered to be a good thing to occur?

Well, due to the magic of binary numbers and operations, our code will happily continue to perform its task of flashing the LEDs without any change in delay or any other disruption, even when the `millis()` register overflows back to 0. The reasoning behind all this takes a bit of time to digest and we don't want to delve into it here. Happily, I wrote two columns some time ago that discuss all of this in excruciating detail (**https://bit.ly/3cPSSBo** and **https://bit.ly/2GrlNQ2**).

A deluge of drips

Our first incarnation of a multi-drip program just focuses on the drips themselves. There's quite a lot to this, so I really do advise you to download the text version of this program and print it out so you can follow along (file **CB-Dec20-03.txt**).

When you peruse this program, you will see many familiar faces in the form of the little utility functions we created in earlier drip sketches, such as `GetNeoNum()`, `CrossFadeColor()`, `BuildColor()`, `GetRed()`, `GetGreen()`, and `GetBlue()`. In fact, apart from these functions and our `setup()` and `loop()` functions, we have only two other functions: `StartNewDrip()` and `ProcessDrips()`.

Before we look at these new functions in a little more depth, there are some new constructs and definitions we need to consider in the form of `typedef` (type definitions), `enum` (enumerated types), and `struct` (structures). The nitty-gritty of these constructs is explored in more depth in this month's *Tips and Tricks* column. For our purposes here, all we need to know is that we've declared an enumerated type called `PixelState` as follows:

```
typedef enum PixelState
{
      NONE,
      DRIP_WAITING,
      DRIP_RISING,
      DRIP_SUSTAINING,
      DRIP_FALLING
};
```

These are the states that we are going to associate with each of our pixels: `NONE` says that this pixel is currently inactive, `DRIP_WAITING` says that we've scheduled this drip to commence at some time in the future, and `DRIP_RISING`, `DRIP_SUSTAINING`, and `DRIP_FALLING` govern the pixel fading up, holding, and fading away again, respectively.

Next, we declare a structure called `Pixel`, which contains all of the attributes we wish to associate with each of our pixels:

```
typedef struct Pixel
{
   PixelState currentState;
   uint32_t   waterColor;
   uint32_t   oldColor;
   uint32_t   newColor;
   int        numSteps;
   int        currentStep;
};
```

Observe that the first of these attributes is the state of the pixel. We will commence with all of the pixels having a state of `NONE`, where these values are assigned as part of our `setup()` function.

There are many different ways in which we might decide to implement our program. One realisation might involve including a `lastTimeLedChanged` field in our `Pixel` structure (similar in concept to the way in which we implemented our 2-LED program earlier in this column). As we will see, however, I decided to adopt a slightly different approach.

The final piece of this portion of the puzzle is where we declare an array called `Pixels[][]` of our `Pixel` structure, as shown below:

```
Pixel Pixels[NUM_COLS][NUM_ROWS];
```

Although it may take a bit of effort to wrap our brains around all this, it's really not as bad as it seems. If we look at things in reverse order, we have an array called `Pixels[][]` that contains the data associated with each our pixels. This data includes things like the state of the pixel, the colour associated with the pixel, and so on.

As we see below, the `loop()` function is actually simpler than the one we employed in our 2-LED program:

```
void loop ()
{
   uint32_t currentTime = millis();

   if ( (currentTime - LastTickTime) > TICK)
   {
      StartNewDrip();
      ProcessDrips();

      Neos.show();

      LastTickTime = currentTime;
   }
}
```

As you may recall from previous programs, we are using a master clock whose `TICK` is set to 10ms. This means that every ten milliseconds we call our `StartNewDrip()` function followed by our `ProcessDrips()` function, after which we display the current values of our pixels and update the variable storing the current time.

If you look at the code, you will see that the `StartNewDrip()` function doesn't always initiate a new drip. We have a global variable `NumActiveDrips`, which stores the number of active drips, and we have a constant `NUM_MAX_DRIPS`, which defines the maximum number of drips that can be active at any particular time. Our `StartNewDrip()` function will only initiate a new drip if we aren't already fully loaded and – even then – it will schedule the new drip to commence at some random time in the future.

Meanwhile, the cunning way in which we've architected the `ProcessDrip()` function means that every stage of the drip is implemented in the same way, fading from one colour to another over a series of steps. When we are waiting for a drip to drop, for example, we spend our time fading from black to black, which – not surprisingly – ends up looking like black. When we fade a pixel up, we fade from black to the randomly selected colour for that pixel. When we hold a pixel in its current colour, we actually fade from that colour to itself. And when we fade a pixel down, we fade from its randomly selected colour back to black.

We aren't going to examine this code in any more detail here. Suffice to say, we can feast our eyes on all of this in action in a video I just captured (**https://bit.ly/33ufl3V**).

Galoshes on!

Thus far, we've been experiencing only rudimentary drip effects (Fig.3a). The final step on our trek through driptopia, the land of drips – at least for the moment – is to add the concept of a splash (Fig.3b). The idea here is that shortly after a primary drip drops, a muted version of the drip colour will appear in the pixels to the north, south, east, and west. These muted versions will persist for a short time after the primary drip fades, after which they too will fade away ('All we are is drips in the wind,' as the progressive rock band Kansas might have sung).

Once again, I strongly advise you to download the text version of this program and print it out so you can follow along (file **CB-Dec20-04.txt**).

The first change to the previous program is that we've modified our `MIN_XY` and `MAX_XY` definitions from 0 to 1 and 11 to 10, respectively. We did this to ensure that our `StartNewDrip()` function won't launch any primary drips in any of the pixels at the outside edges of the array, thereby relieving us of having to perform any jiggery-pokery with regard to any splash pixels that might otherwise appear outside of the array.

The next change is that we've added some additional states to our PixelState enumerated type (the new states are shown in bold):

```
typedef enum PixelState
{
   NONE,
   DRIP_WAITING,
   DRIP_RISING,
   DRIP_SUSTAINING,
   DRIP_FALLING,
   SPLASH_WAITING,
   SPLASH_RISING,
   SPLASH_SUSTAINING,
   SPLASH_FALLING
};
```

We've also added a `FadeColor()` function that we use to take the main drip colour and fade it down to a specified percentage of its original value – this muted version is what we use for our splash pixels.

Last but not least, we've modified the `StartNewDrip()` function to also launch any associated splash pixels, and we've augmented the `ProcessDrips()` function to display these splash pixels. As you will see, the cunning way in which we architected the original (pre-splash) version of our program means that adding the splash effect is really not as difficult as you might have supposed. Once again, we can feast our orbs on all of this in action in a video I just captured (**https://bit.ly/3ljkcer**).

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Max's Cool Beans cunning coding tips and tricks

In this month's main Cool Beans column, we employed some new concepts in the form of `typedef` (type definitions), `enum` (enumerated types), and `struct` (structures). Let's look at these in a little more detail.

Enumerated types (`enum`)

if we wish to implement a finite-state machine (FSM), we will need some way to store its current context (state). One way to do this would be to identify a set of states and associate them with numbers using a set of `#define` statements:

```
#define NONE            0
#define DRIP_WAITING    1
#define DRIP_RISING     2
#define DRIP_SUSTAINING 3
#define DRIP_FALLING    4
```

Later, we might declare a variable called `currentState` as being of type `int` (integer), after which we can perform assignments like:

```
currentState = NONE;
```

And we can perform tests like:

```
if (currentState == NONE)
{
   // More stuff goes here
}
```

This technique is fine and it's not difficult to add more states. However, if you are anything like me, you can easily end up spending a lot of time reorganising things and changing the numbers associated with different states because you want things to be 'just so.'

The `enum` keyword allows us to create a user-defined type comprising a set of named constants called enumerators:

```
enum PixelState
{
   NONE,
   DRIP_WAITING,
   DRIP_RISING,
   DRIP_SUSTAINING,
   DRIP_FALLING
};
```

Observe that no comma is required after the final enumerator, but a semicolon is required after the '`}`' (that is, the closing curly bracket). By default, the enumerators are assigned integer values by the compiler starting with 0. This means that, in the above example, `NONE` will be assigned a value of 0, `DRIP_WAITING` will be assigned a value of 1, and so forth. It's also possible for us to assign our own values. It's even possible for multiple enumerators to be assigned the same value, but that's beyond the scope of our discussions here.

Once we've defined an `enum`, we can declare one or more variables of this `enum` type:

```
enum PixelState oldState;
enum PixelState newState;
```

Also, we can assign values as part of the declaration; for example:

```
enum PixelState oldState = NONE;
enum PixelState newState = DRIP_RISING;
```

Elsewhere in our program, we can assign new values to these variables as we wish:

```
oldState = DRIP_RISING;
newState = DRIP_SUSTAINING;
```

Structures (`struct`)

The `struct` keyword is used to define a collection of data items, each of which may have its own type:

```
struct Pixel
{
   PixelState currentState;
   uint32_t   waterColor;
   uint32_t   oldColor;
   uint32_t   newColor;
   int        numSteps;
   int        currentStep;
};
```

Observe that semicolons are required both after the final field and after the closing curly bracket. Once we've defined a `struct`, we can declare one or more variables of this `struct` type, where these variables may be scalar values or arrays:

```
struct Pixel myFavoritePixel;
struct Pixel myArrayOfPixels[100];
```

Observe that the second example declares an array with 100 elements numbered from 0 to 99. In the case of our multi-drip programs, we actually declared multi-dimensional arrays of these structures, because that's just the sort of guys and gals we are.

Unlike arrays, the individual fields (items) in a `struct` are accessed by name instead of using an integer index:

```
myFavoritePixel.currentState = NONE;
myArrayOfPixels[6].currentState = NONE;
```

Observe that when we are dealing with an array, as in the second example, we also have to provide an integer index to specify which element of the array we are talking about (element 6 in this example).

Type definitions (`typedef`)

The `typedef` keyword is used to assign alternative names to existing data types. If we really dislike the `int` keyword, for example, we could use the following statement, where `int` is the existing data type name and `simon` is the alias:

```
typedef int simon;
```

After this, we can declare new variables with a data type of `simon` if we wish. Obviously, this particular example is a tad nonsensical, but using `typedef` with existing data types can be useful on occasion. Where the `typedef` keyword really comes into its own is when it's used in conjunction with user-defined `enum` and `struct` statements. Let's start by using a `typedef` in conjunction with an `enum`:

```
typedef enum PixelState
{
   NONE,
   DRIP_WAITING,
   DRIP_RISING,
   DRIP_SUSTAINING,
   DRIP_FALLING
};
```

Now, when we come to declare one or more variables of this `enum` type, we can simply say something like:

```
PixelState oldState;
PixelState newState;
```

Compare this to our earlier example where we had to reuse the `enum` keyword. Next, let's use a `typedef` in conjunction with a `struct`:

```
typedef struct Pixel
{
   PixelState currentState;
   uint32_t   waterColor;
   uint32_t   oldColor;
   uint32_t   newColor;
   int        numSteps;
   int        currentStep;
};
```

Now, when we come to declare one or more variables of this `struct` type, we can simply say something like:

```
Pixel myFavoritePixel;
Pixel myArrayOfPixels[100];
```

Compare this to our earlier example where we had to reuse the `struct` keyword.

But wait, there's more...

As always, we've really only scratched the surface with regard to the way in which the `enum`, `struct`, and `typedef` keywords can be combined and deployed, but I think we can all bask in the glow of knowing that we now know enough to be just a little bit dangerous.

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Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

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Jim Gatenby

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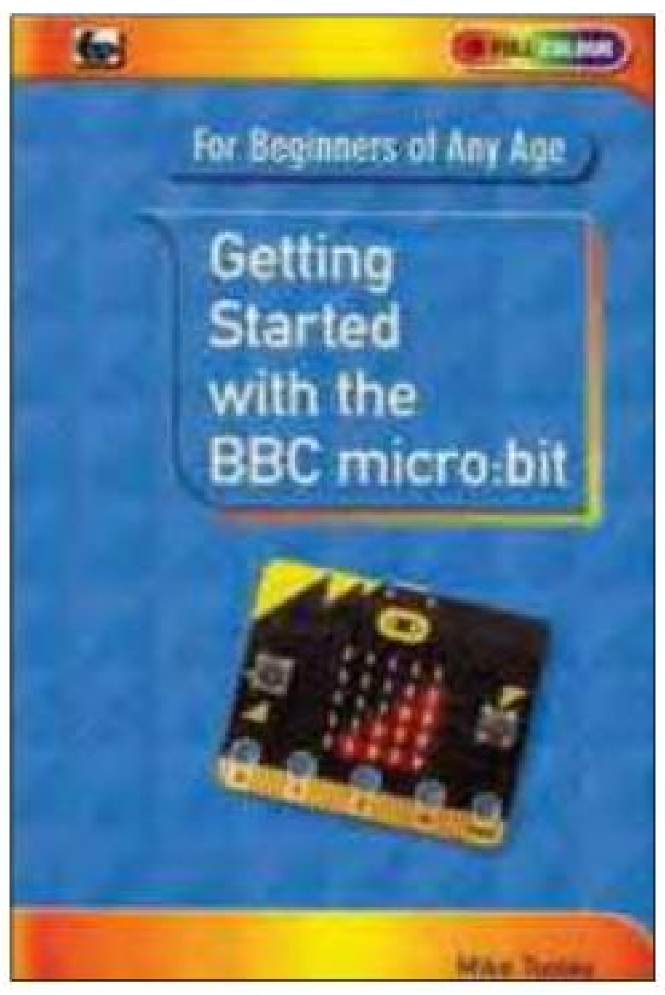

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Mike Tooley

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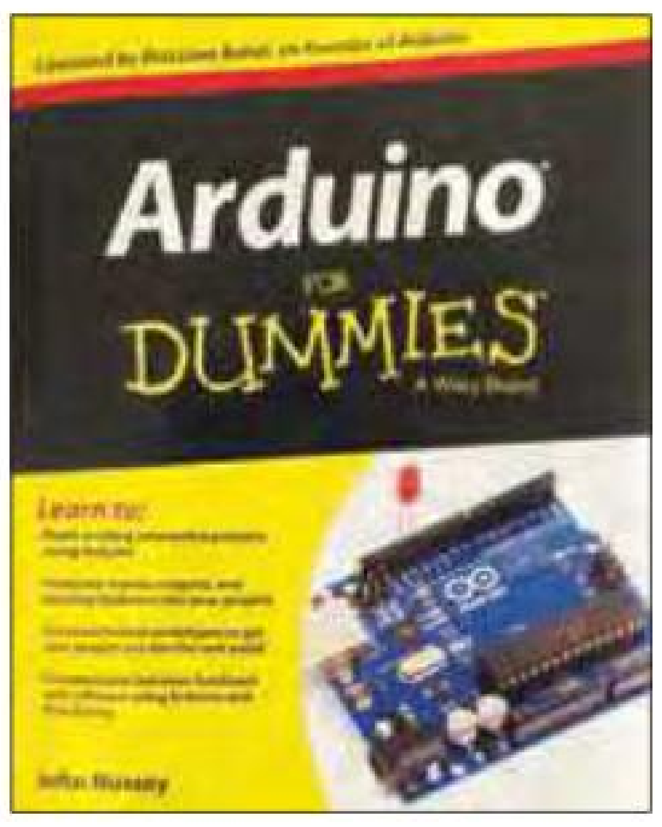

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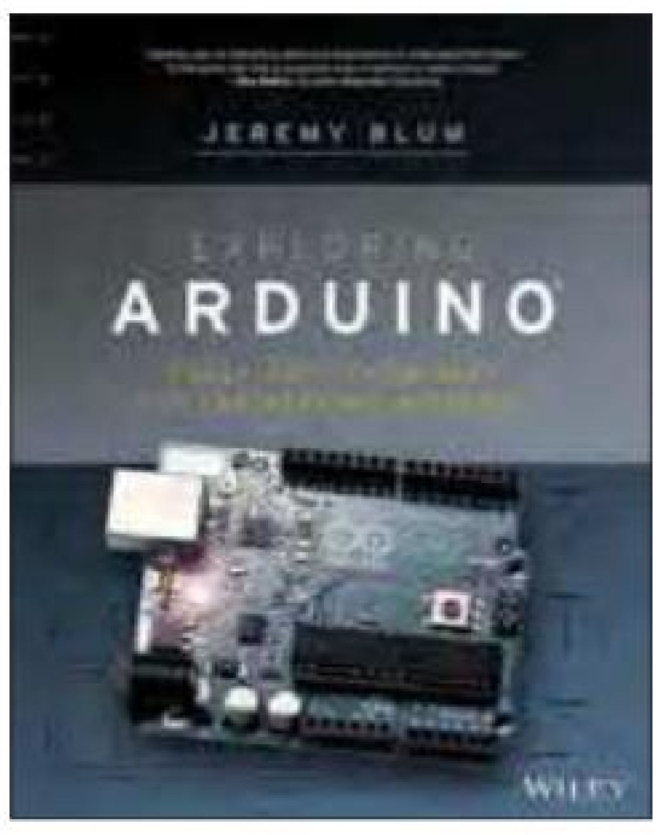

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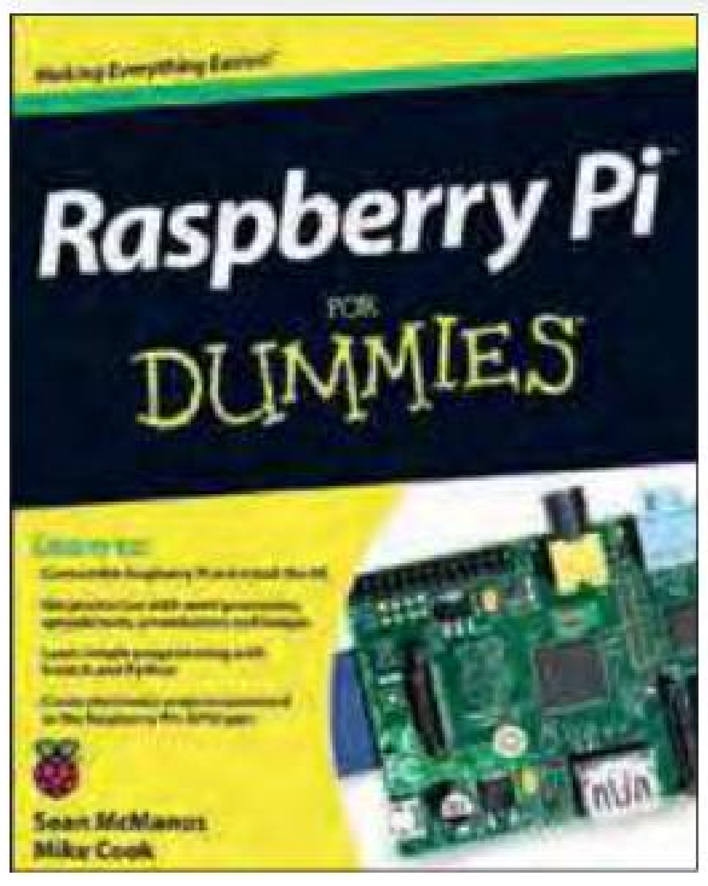

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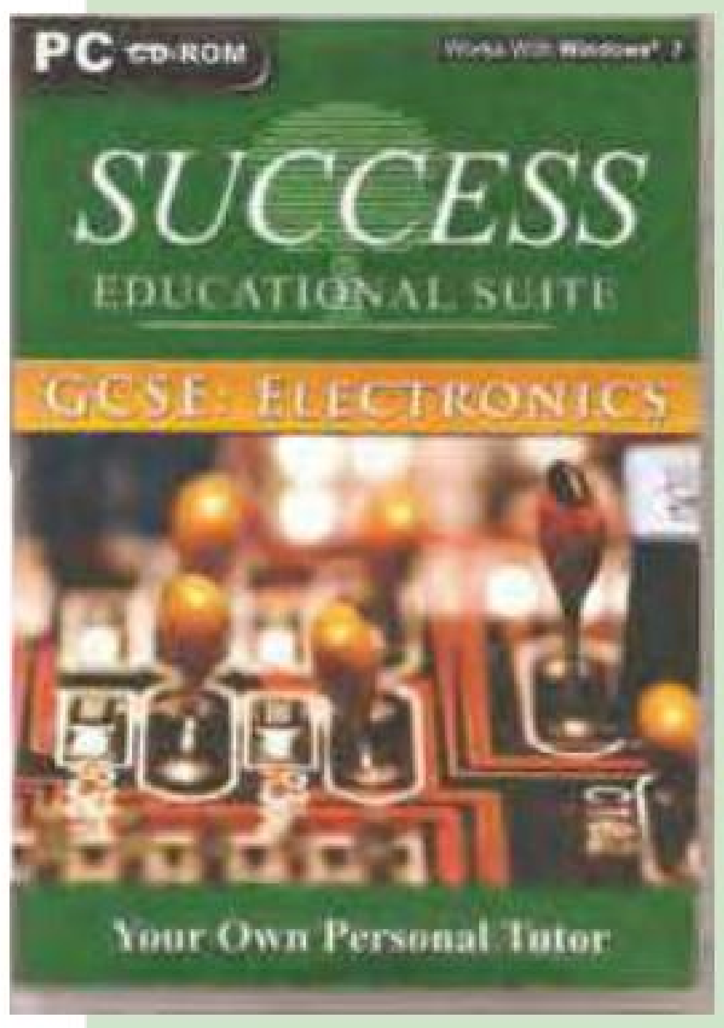

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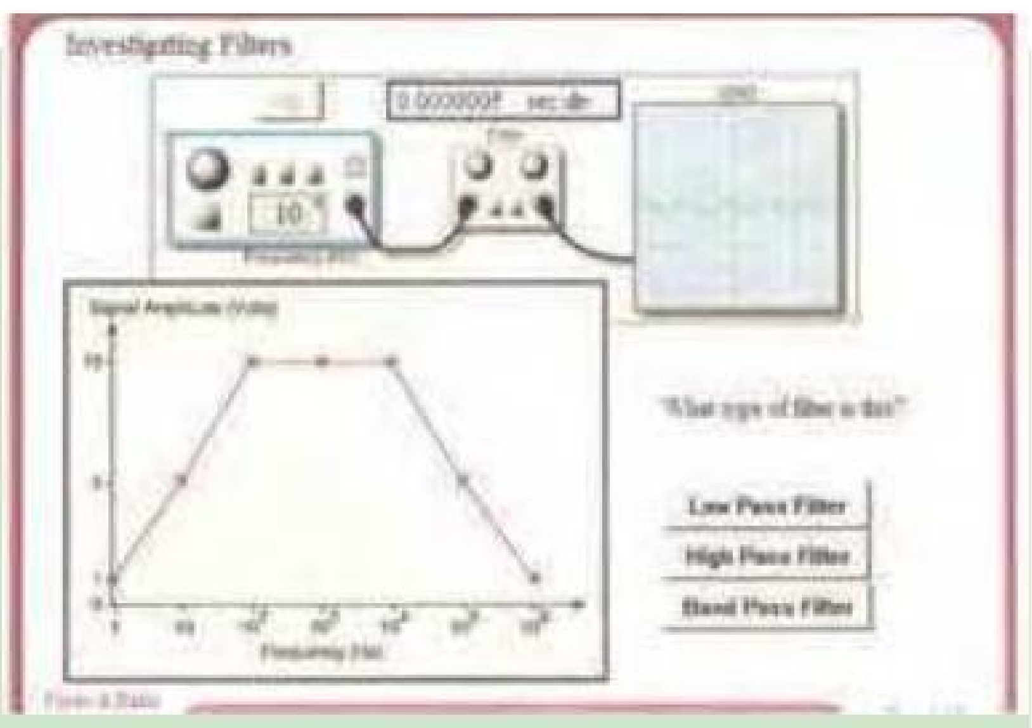

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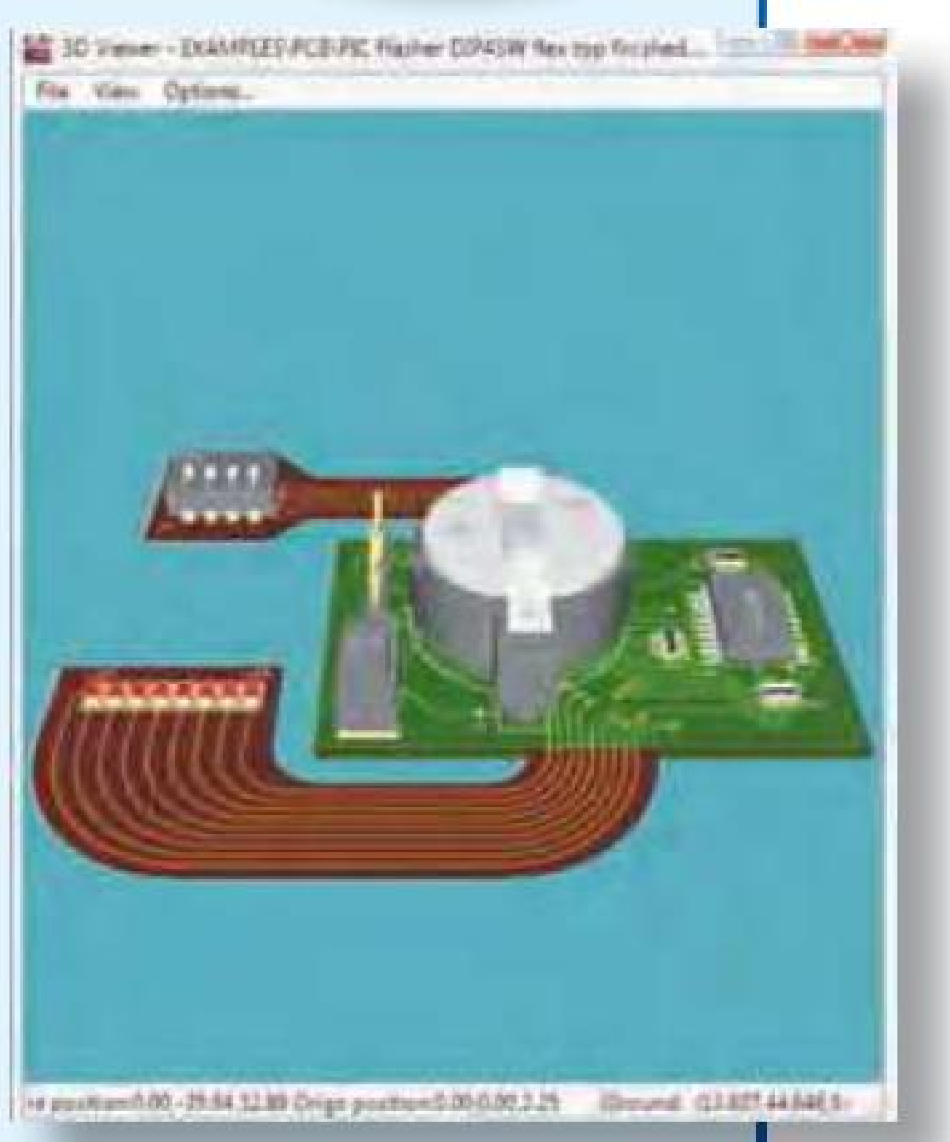

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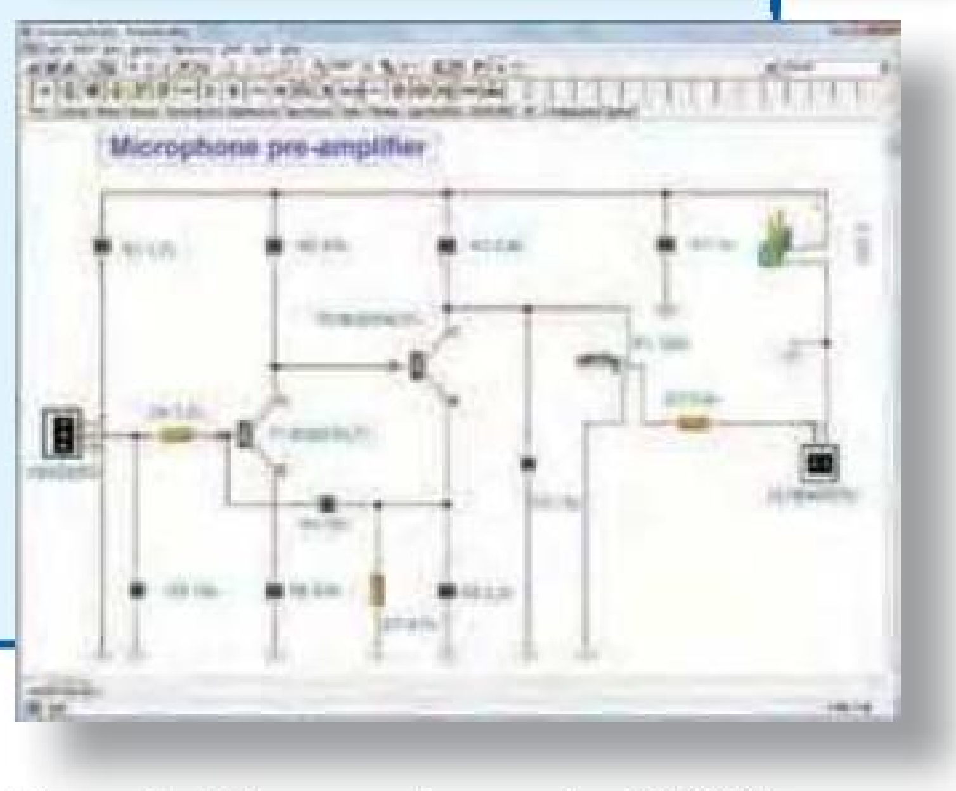

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This *Teach-In* series of articles was originally published in *EPE* in 2008 and, following demand from readers, has been collected together in the *Electronics Teach-In 2* CD-ROM.

The series is aimed at those using PIC microcontrollers for the first time. Each part of the series includes breadboard layouts to aid understanding and a simple programmer project is provided.

Also included are 29 *PIC N' Mix* articles, also republished from *EPE*. These provide a host of practical programming and interfacing information, mainly for those that have already got to grips with using PIC microcontrollers. An extra four part beginners guide to using the C programing language for PIC microcontrollers is also included.

The CD-ROM also contains all of the software for the *Teach-In 2* series and *PIC N' Mix* articles, plus a range of items from Microchip – the manufacturers of the PIC microcontrollers. The material has been compiled by Wimborne Publishing Ltd. with the assistance of Microchip Technology Inc.

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The three sections of this CD-ROM cover a very wide range of subjects that will interest everyone involved in electronics, from hobbyists and students to professionals. The first 80-odd pages of Teach-In 3 are dedicated to *Circuit Surgery*, the regular *EPE* clinic dealing with readers' queries on circuit design problems – from voltage regulation to using SPICE circuit simulation software.

The second section – *Practically Speaking* – covers the practical aspects of electronics construction. Again, a whole range of subjects, from soldering to avoiding problems with static electricity and indentifying components, are covered. Finally, our collection of *Ingenuity Unlimited* circuits provides over 40 circuit designs submitted by the readers of *EPE*.

The CD-ROM also contains the complete *Electronics Teach-In 1* book, which provides a broad-based introduction to electronics in PDF form, plus interactive quizzes to test your knowledge, TINA circuit simulation software (a limited version – plus a specially written TINA Tutorial).

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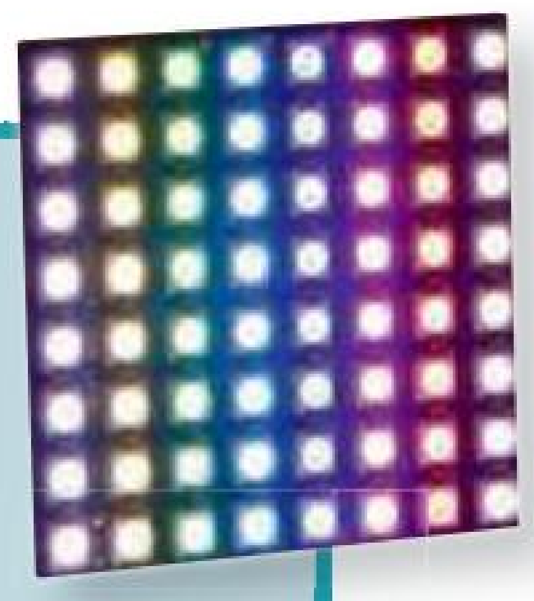
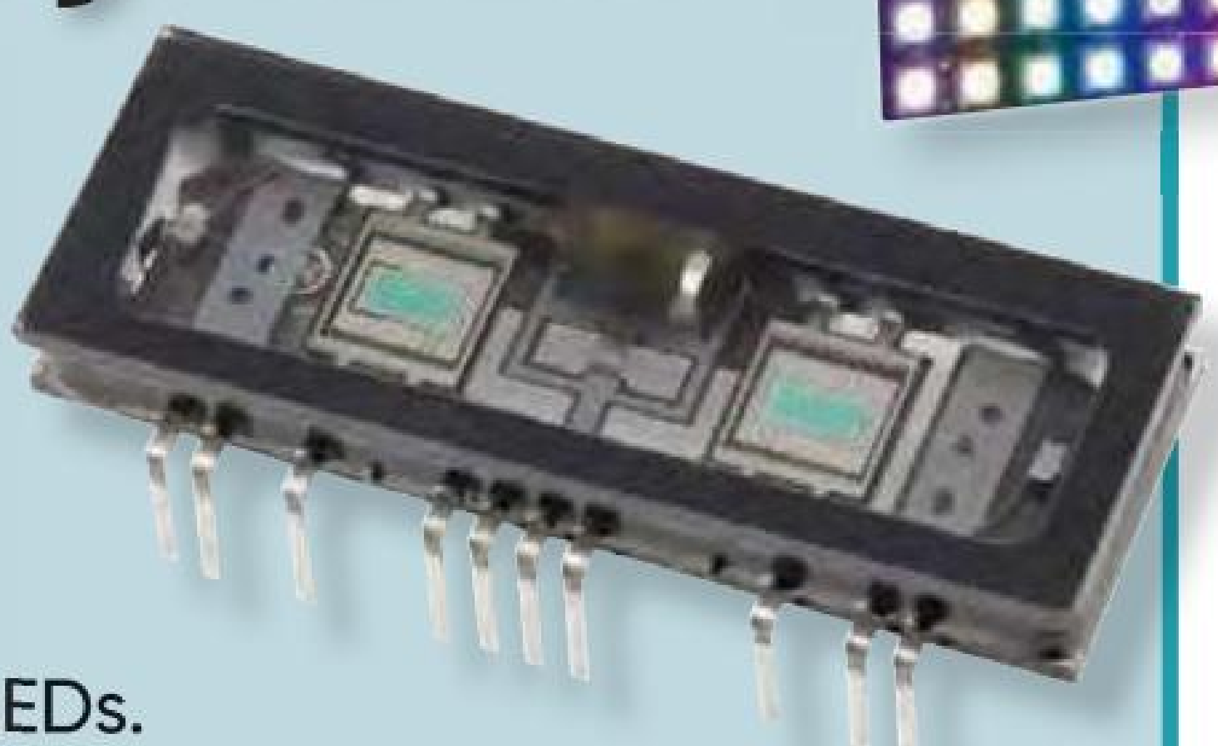


Next Month – in the January issue



Nutube Miniature Valve Stereo Preamplifier

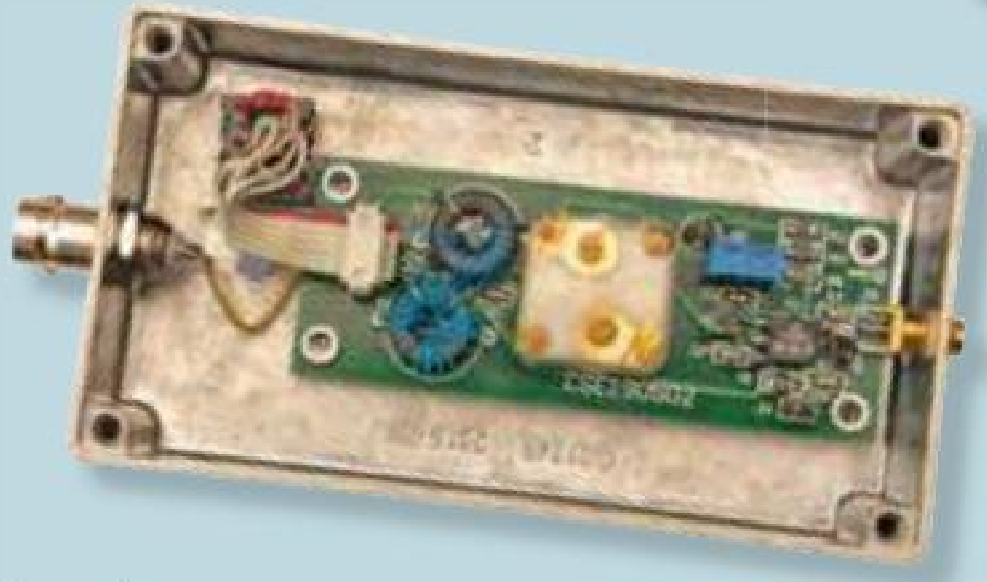
Valves are old hat, right? Not any more, they're not! Korg and Noritake Itron of Japan recently released their Nutube 6P1 twin triode. Its party trick is a very wide range of operating voltages, from just a few volts up to 200V, and meagre power consumption. That makes it ideal for a battery-powered stereo preamplifier.

Using Cheap Electronic Modules

Next month, we're looking at a module with an 8x8 matrix of 64 'intelligent' RGB LEDs. Each LED can display over 16 million different colours, or primary colours at 256 brightness levels. The LEDs are controlled serially via a single wire, and multiple modules can be cascaded to build a much larger display. That makes for all sorts of useful applications.

A Complete Arduino DCC Controller

Digital Command Control (DCC) is a great way to control multiple trains on a model railway layout. Unfortunately, commercial DCC systems can be quite expensive. Here we present an Arduino-compatible Controller shield that can form the basis of a DCC system. It can also be used as a DCC booster or even as a high-current DC motor driver.



Tunable HF Preamplifier with Gain Control

This simple tunable preamplifier greatly improves SDR HF performance. It has (optional) gain control and can run off a 5V supply or phantom power.

PLUS!

All your favourite regular columns from *Audio Out*, *Cool Beans and Circuit Surgery*, to *Make it with Micromite*, *Practically Speaking* and *Net Work*.

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